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---TECHNICAL REPORT---

THE NATION'S LABORATORY FOR ADVANCED AUTOMOTIVE TECHNOLOGY

WINNER OF THE 1995 PRESIDENTIAL AWARD FOR QUALITY

No. 13529

ENGINE INTAKE AIR DUST DETECTOR
REQUIREMENTS AND PERFORMANCE

March 1991

By Martin B. Treuhaft
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TSI was awarded this 15-month, phase II, SBIR contract in July 1989. The objective was to improve and test the prototype dust detector developed in Phase I. Design improvements included simplifying and ruggedizing the design. Extensive environmental testing was to be performed. Ten units were to be delivered to TACOM at the end of the contract.

TSI was successful in both the design improvement and testing. This final report summarizes TSI's efforts. The dust detector's theory of operation is given, as well as a description of its design. Results of the environmental tests are also provided.

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ENGINE INTAKE AIR DUST DETECTOR REQUIREMENTS AND PERFORMANCE

March 1991

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1.0. INTRODUCTION

This final technical report, prepared by Southwest Research Institute (SwRI) for the U.S. Army Tank-Automotive Command (TACOM) under Contract DAAE07-86-C-R043, describes an analytical and laboratory program to evaluated on-vehicle, real-time dust detectors which would monitor engine air quality and provide a warning when unacceptable levels of dust are encountered. Dust detector performance requirements were developed through laboratory testing of several military air cleaner systems which defined the particle size distributions and concentration levels typically found downstream of military air cleaners during normal and abnormal filter operation. These performance requirements were translated into a "go"/"no-go" specification based on particle size, concentration, and response time.

Commercially available, off-the-shelf dust detectors were sought that could meet this specification and which showed potential for successful on-vehicle integration and operation. Although no such units were found, several units and technologies were identified that showed potential for meeting the necessary functional requirements, while also showing potential for on-vehicle integration. These pre-prototype units and technologies were evaluated through a series of trade-off studies and bench tests to measure their functional response to specific environments and to assess their overall potential for the given application. The more promising candidates were subjected to full-scale laboratory testing on a 5-ton truck mock-up.

As a result, one unit was identified as the unit of choice (HIAC/ROYCO second round prototype) based on its approach and performance in making the particle sizing and concentration measurement, and on its potential for hardenability to allow successful on-vehicle integration and operation. This unit should be pursued through rapid prototype development, leading to full-scale demonstration and testing.

In addition to the analytical and experimental work, field visits were made to several M60 units to discuss M60 "dust detector" usage and to obtain field/user input concerning the dust detector concept and its method of implementation and utilization. There was consensus that a reliable, real-time dust detector would be a welcomed item, which could help reduce or eliminate dust-related engine failures resulting from faulty air induction systems.

2.0. OBJECTIVES

Major objectives of this project were to develop criteria for an on-vehicle, real-time dust detector which would monitor engine induction air quality and provide a warning when unacceptable levels of dust are encountered; to determine the levels of protection afforded by standard military air cleaner systems as a function of filter condition and engine/vehicle operating environments, with respect to the size and concentration of particles passed to the engine; to determine the levels of protection necessary to provide adequate engine life; to define the operating and performance requirements for an on-board dust detection system; and to identify and evaluate commercially available systems and technologies (if any) with potential for meeting these requirements.

3.0. CONCLUSIONS

3.1. Dust Detector Need and Application.

A real-time, on-board dust detector is needed and wanted by field units to warn crews when malfunctioning air induction components allow too many dust particles to enter the engine. In this manner, air induction problems can be detected and resolved early, before significant engine damage is encountered. In addition, the dust detector will make it easier for troops to adequately maintain the air induction (filtration) system, and this should result in reduced (unscheduled) engine maintenance and vehicle downtime, and thereby improve overall operational readiness.

3.2. Current M60 Dust Detector Technology.

The current M60 dust detector is not useful or beneficial because it does not operate in real-time, it is not reliable, and it does not respond to actual in-duct dust concentration levels. Overall circuit reliability is low; that is, the warning light does not always trigger when it should or, conversely, it triggers when it should not. As a result, even though crews pay attention to the warning light (when it works), it is usually too late as far as preventing dust ingestion is concerned. Also, because the warning light often false triggers (because of electrical shorts and other problems), user confidence is lowered, sometimes to the point where the dust detector is ignored, or at least, not always used properly. The real-time dust detectors currently under consideration will do away with many of the problems. With respect to vehicle integration and operation, the major concerns of the M60 field units are reliability, functionality, and real-time responsiveness.

3.3 Dust Detector Triggering Criteria

Triggering criteria are dependent on sensor type and vehicle air filtration system. For the vehicles evaluated in this project (2½- and 5-ton truck, and M2/M3), the following triggering criteria are applicable:

Particle size	:	7 μm
Numerical concentration	:	1200 particles per cu ft air
Mass concentration	:	0.75 μg per cu ft air
Response time	:	5 sec with false signal discrimination (see 5.2.1.2.)

3.4. Downstream Particle Size Characteristics

A. Because of differences in typical downstream particle distributions for different air cleaner systems, if one set of triggering criteria is to be applicable for all systems, the threshold values will be dictated by the least efficient system.

B. Because filters pass a much larger percentage of particles when new than once dust loading starts, early filter performance becomes a controlling factor in setting threshold values.

C. Downstream distributions for particles in the 3-5μm range tend to represent the onset of discrimination ability between normal and abnormal air cleaner operation, with the 5μm value providing both better discrimination and better relevancy with respect to the presence of larger (greater than 5μm) downstream particles.

D. When a normal filter loads with dust, the number of downstream particles of all sizes rapidly decreases, although the proportional decrease for the larger particles is greatest. For the abnormal filter, the relative distributions change much less over time, with later distributions not differing significantly from those for the clean filter case. This can present a problem in setting threshold values for size and concentration.

E. There is high statistical likelihood, because of the nature of typical environmental dust distributions, that detection at the 5μm level will accurately account for the presence of larger particles, even though the larger particles will be present at much lower concentrations.

3.5. Importance of the In-Duct Concentration Measurement

The dust detector must discriminate based on actual in-duct concentration levels. This point was not well understood by many of the dust detector manufacturers, who based concentration on "artificial" levels resulting from the direct use of the detector's sampling flow rate or an assumed average engine rpm, for example.

3.6. Response Time

A response time requirement of 5 seconds would allow time for signal processing to discriminate among false signals, "one-time" sightings, and abnormal operation. A "flexible" response time may be needed to avoid false triggering for dust concentrations near the threshold level.

3.7. "Universality"

TACOM's desire for a "universal" dust detector applicable to "all" Army tactical and combat vehicles places significant restrictions on the specifications and triggering criteria for dust detector performance. Nevertheless, a universal dust detector is feasible.

3.8. The Impact of Filter Performance on "Universality"

A major problem in specifying triggering criteria for a "universal" dust detector is the presence of large numbers of downstream particles which typically penetrate a new (clean) filter element and the relatively high number of small particles which will be present throughout the filter's operating life. Quantitatively, the number and size of these particles are generally vehicle specific because they are a function of air cleaner type.

3.9. The Impact of Duct Configuration

Vehicle interfacing, primarily duct configuration and sensor placement, can have a significant impact on overall dust detector response and performance. Hence, a single "universal" dust detector for "all" Army vehicles may not be appropriate.

3.10. The Impact of Filter Performance on Long-Term Operation

Air filter elements used to protect engines on military vehicles allow significant particle penetration when operating in highly dusty environments, even when operating properly. Therefore, the dust detector must meet very stringent triggering criteria so as not to (false) trigger during normal filter operation, and it must be able to sustain operation during long-term exposure to dust without component degradation.

3.11. Discriminating Normal-Abnormal Filter Operation

In general, there is little problem distinguishing between a faulty air filter system and a properly operating system after the filter(s) has undergone some degree of dust loading. However, the ability to discriminate system performance for newer (cleaner) filter elements is more difficult because of the large amounts of dust of varying particle sizes that penetrate before a dust cake is established. This is particularly important when discrimination is to be based on a single particle size-concentration-time criterion (for instance, when the concentration of particles > **x** μm exceeds **y** particles per cubic foot air for **z** seconds).

3.12. Triggering Criteria "Range"

A truly meaningful definition of the dust detector's triggering criteria depends on the particle sensing technology employed. The result event, however, must be the same for all detectors when exposed to a given dust distribution. Specifying a "range" of criteria for concentration and response time that are somewhat technology dependent provides a meaningful triggering criteria without favoring a particular technology or method of approach. This is most important when attempting to discriminate distributions which lie near the concentration threshold.

3.13. "Go"/"No-Go" Operation

The dust detector should be unobtrusive to normal vehicle operation and operate on a "go"/"no-go" basis. The dust detector's triggering specification should include a margin of safety against false triggering.

3.14. Environmental Hardenability

The dust detector must meet all requirements for on-vehicle operation; in particular, those for operating temperature, shock and vibration, electromagnetic interference, and electrical interfacing. None of the dust detectors evaluated met these requirements because, for the most part, they were prototypes intended to demonstrate function and response to particles, rather than environmental hardenability.

3.15. Dust Detector Availability

No commercially available, off-the-shelf dust detectors were available at the start of the project; however, several instruments and technologies were identified which showed potential for meeting the particle sensing requirements for an engine induction air warning system. All units will require repackaging to provide sufficient climatic, shock, and vibration tolerance and to provide for interfacing with on-vehicle electrical systems.

3.15. HIAC/ROYCO; the Unit of Choice

Of the dust detectors evaluated, the second round, HIAC/ROYCO prototype detector (technology) with its approach to particle sizing and concentration, is the unit of choice.

A. This detector demonstrated an ability to function as a "go"/"no-go" particle discriminator, with good potential for successful on-vehicle integration.

B. The HIAC/ROYCO technology appears hardenable to withstand rugged military environments, and adaptable to allow installation on a variety of vehicles.

C. The HIAC/ROYCO unit was the only detector to properly address the concentration issue. The other units, which measured particle size but which did not relate the particle size distributions to the actual particle concentration in the duct, did not entirely address the triggering criteria, and therefore will not fully function as dust warning systems.

3.17. Evolving Technologies

Particle sensing technology is rapidly evolving, with major advances being made in measurement sensitivity, response range, miniturization, and potential for hardenability to withstand sustained operation in harsh operating environments.

4.0. RECOMMENDATIONS

4.1. Prototype Development and Design Verification.

Because it measures particle size <u>and</u> concentration with a single (in-situ) sensor, the HIAC/ROYCO preliminary prototype should be actively pursued, with rapid prototype development and bench evaluation being major priorities.

4.2. Full-Scale Laboratory Testing and Field Evaluation.

Following successful prototype development and bench testing, the HIAC/ROYCO detector should undergo full-scale laboratory testing, followed by field evaluation and demonstration.

4.3. Vehicle Interfacing.

A study should be made of all tactical and combat vehicles that are likely to receive dust detectors to determine specific interfacing requirements with respect to duct configuration and its potential impacts on sensor placement and operation. This is necessary to determine if the dust detector can be universally applied or if special interfacing requirements may be needed.

4.4 Analyses of Air Filter Systems

Analyses of air filter systems from vehicles other than those analyzed in this project should be conducted to determine the extent to which the triggering criteria established herein are applicable (to other vehicles).

4.5. Future Systems.

Because particle sensing technology is rapidly evolving, an effort should be made to stay abreast of new developments and instruments in order to monitor their potential for the dust detector application. This is particularly relevant in view of TACOM's desire for a "universal" detector for application to all tactical and combat vehicles.

5.0. DISCUSSION

5.1. General

Airborne dust has long been recognized as a major cause of engine wear, particularly for vehicles that operate in unusually dusty environments, such as construction, mining, and the military. Because abnormal wear can have a significant effect on engine life, a large effort has been made over the years to improve intake air quality. Therefore, a primary goal of this project was to develop criteria for an on-vehicle dust detector which would monitor engine induction air quality and provide a warning when unacceptable levels of dust are encountered. Major objectives were to determine the levels of protection afforded by standard military air cleaner systems with respect to the size and concentration of particles physically passed to the engine, to determine what levels of protection are necessary to provide adequate engine life, to define the operating and performance requirements for a dust detection system, and to identify and evaluate commercially available systems (if any) with potential for meeting these requirements. These objectives were met by 1) analyzing the degree of dust protection afforded by typical air cleaner systems when operating properly and with induced faults; 2) by considering the level of dust protection required for a given engine or class of engines; 3) by surveying the market for prime candidates considering the operating and functional requirements, state-of-the-art, cost, mode of operation, likelihood for successful on-vehicle integration, and other instrumentation parameters; 4) by performing trade-off studies amongst potential candidates; 5) by conducting laboratory tests on the more promising candidates under simulated operating conditions to measure functional response to specific environments;

and 6) by determining each dust detector's potential and the potential of specific technologies to be sufficiently hardened to allow operation on military tactical and combat vehicles.

While it was considered unlikely that an off-the-shelf detector would be suitable for immediate on-vehicle integration and utilization, it was not unreasonable to expect that several commercial units could meet the particle sensing requirements for an engine induction air warning system. This did not mean that commercial units would not be available, per se, but rather that prime candidates would likely require some degree of repackaging to provide sufficient climatic, shock, and vibration tolerance and to provide for interfacing with on-vehicle electrical systems. It was also likely that several modifications would be required to reduce unit cost and to allow for hands-off operation. For example, several features and outputs typically found on laboratory or test instruments could be eliminated, such as analog and digital readouts, sampling period and particle range selectability, and such. Automatic self-calibration, if appropriate, could be accomplished with engine start-up and internal monitoring could be included to assure proper calibration during engine-vehicle operation. Threshold levels could likely be preset or built in so that monitoring could become a simple "go"/"no-go" type of process.

From a filter performance/engine wear point-of-view, two stream parameters were of primary concern, namely dust concentration level and dust particle size. Since all military and commercial engine air filters pass some dust under normal operating conditions, the dust detector must recognize specific threshold conditions in order to eliminate false signals, which would reduce operator confidence and eventually reduce the system's usefulness. These threshold conditions concerned both dust concentration (the amount of dust per given volume of air) and particle size range (particle sizes associated with normal and abnormal filtration and sizes that are harmful to the engine). A major problem in specifying the triggering criteria was the presence of large numbers of particles which typically penetrate a new filter.

Clearly, there are numerous parameters by which a particle or suspension of particles can be characterized, including size, dispersion of sizes, shape, surface area, chemical composition, electrical charge density, and such. However, the parameters of major importance as far as this program was concerned, were primarily particle size, and collectively, concentration. Once these parameters were specified; that is, once acceptable and unacceptable values for particle size and concentration downstream of the filter were known, a meaningful dust detector requirement could be specified. For this reason, considerable effort was expended to measure the downstream environments in terms of

particle size and concentration for three military air cleaner systems. In fact, it was the performance of these systems, over time, which directly indicated the threshold or sensitivity level of downstream particles below which normal filter operation could be assumed, and conversely, above which some type of system failure was predicted. Using these values, and including an error bound to avoid false triggering, led to a "go"/"no-go" type of triggering criteria for the dust detector. It is important to realize that downstream particle parameters were measured as a function of time (that is, as a function of filter dust loading) because typically, both particle size and concentration level change with cake build-up during dust loading. Furthermore, since these parameters are likely to be system (and hence, vehicle) dependent, three different types of military air cleaner systems were evaluated, including single and two-stage configurations: 2½-ton truck, single stage; 5-ton truck, two-stage, non-scavenged; M2/M3, two-stage, scavenged.

Examining different types of systems was particularly meaningful when induced faults were considered. For instance, an induced fault in a 2½-ton truck system, which only had a single filter element, was expected to, and did, produce different downstream parameters than the same induced fault in a 5-ton truck or M2/M3 system, operating with their standard precleaner. Not only did these systems represent different technologies as far as their approach to air filtration was concerned, but they also employed different technologies with respect to their filter media. Because it was desirable to specify a single dust detector that could be used on almost all Army vehicles, downstream particle data for the 5-ton truck and M2/M3 systems became the controlling parameters.

In discussing particle size, distinction must be made between aerodynamic and physical size. Aerodynamic size is defined as the diameter of a unit density sphere with the same settling velocity as the particle in question, regardless of its shape and density. It is an important parameter in determining particle behavior in an air stream; hence, knowledge of this parameter is often preferred to any of the geometric diameters when considering particle deposition by inertial forces, such as removal by inertial precleaners or deposition in engine ducts and sampling lines. On the other hand, geometric parameters; that is, actual physical size and shape, are fundamentally important to engine wear. It was therefore important that aerodynamic diameters, if measured, be correlated to physical particle sizes during experimental work, both in measuring filter throughput and in assessing instrument performance. This correlation was usually handled mathematically in a fairly straightforward manner.

In order to investigate and somewhat quantify the performance of the early instruments, a trade-off study was conducted to rank relative performance and to measure performance

against certain minimum requirements. Since most of the early instruments were laboratory prototypes, the trade-off study was aimed at demonstrating proof-of-concept with respect to particle sensing capability and inferring overall system potential, including prospects for hardenability and vehicle integration. The initial trade-off study was supported by first round testing. Even so, at that time, it was not possible to determine a "best" dust detector because the ranking system showed several units to be very close with respect to performance and potential for vehicle integration. It was possible, however, to identify problem areas and specific modifications and adjustments that were needed. This information was conveyed to the manufacturers and plans were made to conduct second round tests on the upgraded units. It was anticipated that second round testing would lead to a definitive ranking of the remaining detectors via an upgraded trade-off study. As it turned out, second round testing narrowed the field to three units, which were further evaluated on a full-scale 5-ton truck mock-up.

Testing was conducted in three stages or rounds. In stage one, preliminary bench testing was accomplished on pre-prototype units to assess feasibility and to determine potential applicability with respect to dust detector requirements and project objectives.

Units successfully completing round one were subjected to a second series of tests in round two. The purpose of these tests was to measure how well performance was improved as a result of modifications by the manufacturers in response to specific deficiencies identified in round one. Following second-round testing, three units were subjected to full-scale laboratory testing involving a mocked-up 5-ton truck air cleaner system. The major objective of this test was to investigate dust detector performance in conjunction with full-scale vehicle hardware, in a controlled environment which could be adjusted to simulate numerous field and air cleaner operating conditions. Using actual vehicle hardware allowed the detectors to be exposed to flow and dust conditions closely representing various stages of in-service operation.

During the project, field visits were made to four M60 installations to discuss M60 dust detector usage. The purpose was to obtain field/user input concerning the dust detector concept and its method of implementation and utilization. It was particularly important to address specific field concerns and gain additional information with respect to user expectations and requirements. Results from these visits were essentially the same, namely, there was consensus that a reliable, real-time dust detector would be a welcomed item, which could help reduce or eliminate many problems and much of the damage resulting from faulty air induction systems. Key points of discussion emphasized reliability, functionality, and real-time responsiveness.

A major concern throughout the project was the potential impact of duct configuration and probe/sensor placement on sensor response, particularly in the context of TACOM's desire to develop a "universal" dust detector for "all" Army vehicles. As a result, this subject was carefully studied at SwRI and by others closely associated with the project.

Another concern was the need to measure or at least to relate measured results to actual in-duct concentration levels. This issue was repeatedly discussed with the manufacturers; however, in the end, only one unit actually measured in-duct concentration directly. In conjunction with this issue, the issue of sampling, that is, of providing a representative sample of the true in-duct environment to the sensor was carefully considered. Because of the sampling strategies chosen by many of the manufacturers, and because of the need for the dust detector to function properly under variable airflow conditions, this issue became an important factor in the overall evaluation.

The dust detector criteria and requirements were continually critiqued and refined throughout the project, and several attempts were made to redefine and clarify the numerical concentration values given in the early dust detector specification. As noted, particle sensing requirements and triggering criteria for the dust detector were established in response to experimentally determined size and concentration levels for dust particles which were expected to enter an engine when operating in dusty environments with various degrees of air filtration. Specific threshold values were determined by carefully analyzing laboratory data which measured downstream particle distributions as a function of service life and filter condition for three different military air cleaner systems. Data were collected under normal and abnormal (induced fault) filter operation. Minor compromises were accepted so that one set of triggering criteria could be developed. Since the test data were likely to cover the major range of interest as far as overall air cleaner performance was concerned, it was concluded that the triggering criteria should apply to most Army vehicles.

Stating the criteria, however, was not entirely straightforward because a truly meaningful specification depends somewhat on the particle sensing technology employed. As a result, a more general specification concerning particle concentration was eventually developed.

5.2. Dust Detector Requirements

An early objective was to determine the dust detector's triggering requirements with respect to the downstream particle size distributions and concentration levels typifying normal and abnormal filter operation. Since it was desirable that a single triggering

criteria cover all vehicles, if possible, it was important to determine what impact different air cleaner designs and their state-of-the-art would have on potential triggering requirements. Accordingly, the triggering criteria were developed from data collected during standard laboratory filter testing (using zero visibility dust, 0.028 grams per cubic foot air) of three different military air cleaner systems, during which downstream particle size distributions and concentration levels were measured and analyzed as a function of filter dust loading.

One of the main problems in specifying the triggering criteria concerned the presence of the large number of particles which typically penetrate a new filter. Because of the need to balance efficiency and service life, filter element designs have evolved which allow considerable particle penetration when the clean filter element is placed in service and initially exposed to dust. While separation efficiency increases significantly as the filter loads with dust, reducing both the concentration and mean size of the particles still penetrating the media, relatively large concentrations and sizes must be contended with during early stages of the new element's life. In addition, it is likely that the dust detector will have to contend with a rather large number of relatively small particles throughout the filter's entire operating life.

Respecification of the filter element's initial efficiency requirement could help correct this problem; however, this is not likely to occur because it would probably have an adverse impact on service life. One can expect, therefore, that air filter elements used to protect engines on military vehicles will allow significant particle penetration when operating in highly dusty environments, even when operating properly. For this reason, the dust detector must meet very stringent triggering requirements so as not to trigger during "normal" system operation and yet remain sensitive enough to trigger at the onset of "abnormal" filter operation. Furthermore, it means that many components used in the dust detector will be subjected to a high number of dust particles during normal operation and, if the components are not designed properly, this could easily degrade their performance over time.

The two major problems encountered in attempting to specify threshold values were, therefore, 1) the desire to establish one set of values which would be independent of any particular air cleaner or vehicle system, and 2) the need to accommodate clean filters, which inherently pass a much larger number of particles early in their loading history, without compromising detection of a faulty or substandard system. In general, there was little problem distinguishing between a faulty system and a properly operating system after the filter(s) had undergone some degree of dust loading. The ability to distinguish

between a new (clean) filter element and a faulty system, however, was less obvious in terms of the particle size-concentration profile, particularly when the objective was to discriminate performance using a single-size concentration value.

5.2.1. Selection of the Proper Threshold Value. A major task in specifying operational requirements for the dust detector concerned selection of appropriate thresholds or triggering values for particle size discrimination and dust concentration, as a function of particle size. This was a critical step because these values could directly affect the type of technology that might be used in the dust detector, and because the triggering level must be sensitive enough to discriminate between normal and abnormal filter operation over the filter's life cycle without allowing excessive engine wear or false triggering. In addition, the threshold values had to be consistent with 1) TACOM's desire to establish one set of values which would be independent of any particular air cleaner system, 2) the need to accommodate the clean filter system which inherently passes a high number of particles early in its loading history, without compromising the detection of a faulty or substandard system, and 3) the need to maintain simplicity in terms of a "go" or "no-go" type of device in order to minimize cost and improve reliability. To resolve the conflicts inherent in these requirements, numerous laboratory tests were run on three different air cleaner systems to characterize typical downstream particle parameters as a function of normal and abnormal filter operation. In addition, a literature search was conducted to determine the impact on engine wear caused by inlet air dust ingestion, and a study was accomplished to develop a sense of correlation between real world dust environments likely to be encountered by combat vehicles and the laboratory environment used to test and develop commercial and military air cleaner systems.

The result of these activities can be summarized as follows:

1. Because of differences in typical downstream particle distributions for different air cleaner systems, if one set of triggering values is to be applicable for all systems, the threshold values will be dictated by the least efficient system.

2. Because filters pass a much larger percentage of particles when new than once dust loading starts, early filter performance becomes a controlling factor in setting threshold values.

3. Downstream distributions for particles in the 3-5μm range tend to represent the onset of discrimination ability between normal and abnormal air cleaner operation, with the 5μm value providing both better discrimination and better relevancy with respect to the presence of larger (greater than 5μm) downstream particles.

4. When a normal filter loads with dust, the number of downstream particles of all sizes rapidly decreases, although the proportional decrease for the larger particles is greatest. For the abnormal filter, the relative distributions change must less over time, with later distributions not differing significantly from those for the clean filter case. This can present a problem in setting threshold values for size and concentration.

5. A response time requirement of 5 seconds would allow time for signal processing to discriminate among false signals, "one-time" sightings, and abnormal operation.

6. There is high statistical likelihood, because of the nature of typical environmental dust distributions, that detection at the 5μm level will accurately account for the presence of larger particles, even though the larger particles will be present at much lower concentrations.

7. Even though there is relatively little concrete data available in the literature quantifying engine wear as a function of specific (ingested) dust parameters, and even though what is available is predominantly engine-specific, it is fairly certain that particles in the 5 to 20μm range will be cause for concern, with the extent of concern depending on specific size, concentration, composition, shape, surface properties, and such. Even if the most aggressive particles lie in the upper range, and even though 5μm particles may cause less wear than 20μm particles, their impact can be significant. (A recent SwRI experimental project found the onset of ring wear in a modern industrial diesel engine to be sensitive to particles in the 2-3μm range at dust concentration levels as low as 50μg of dust per cubic foot air.)[1]

Based on these considerations, the following threshold (triggering) levels were recommended (April 1987):

Particle size :	5μm (later changed to 7μm)
Concentration:	0.25 x 10^6 particles per cu ft air (later changed to under 10,000)
Response time:	5 seconds with false signal discrimination

This meant that the dust detector must trigger whenever the concentration of 5μm particles exceeded 0.25 x 10^6 particles per cubic foot of air for a period of 5 seconds. It was noted that these values may be affected by probe placement, which should be as close to the engine intake as possible to take into account potential leaks in the air cleaner ducting, as these leaks are also critical to engine wear. Consideration should also be given to methods of on-vehicle interrogation, including self-test and periodic validation. It is noteworthy that the 5μm particle size level was changed to 7μm after discussion with TACOM. It is also noteworthy that the 0.25 x 10^6 particles per cubic foot concentration criteria was improperly stated and this value was changed later in the program to be less than 10,000 particles per cubic foot. The particle size change was made to give a larger margin of safety against false triggering without greatly compromising engine wear.

In summary, the requirements of April 1987 were based on extensive laboratory testing of several military air cleaner systems which established typical downstream particle size distributions and concentration levels under normal and abnormal (induced fault) operation, and on the potential impact of these distributions on engine wear. Analyses of downstream particle distributions showed that triggering at the threshold values given would provide sufficient warning against unacceptable amounts of dust being ingested into the engine. These performance requirements were conveyed to the potential dust detector manufacturers.

The dust detector requirements and triggering criteria were reviewed and critiqued often throughout the project. In particular, several attempts were made to clarify the numerical concentration value given in the dust detector specification. The confusion stemmed from the way the (April 87) requirement was stated and what it meant. As given, the requirement was a singular value for the total number of particles per cubic foot for all particles equal to or exceeding a given size, 7μm. As developed, this number represented a specific distribution value normalized to Δlog dp, and as such, it should not have been used without showing the distribution or stating the slope of the distribution in the area of interest. For example, the value of $\Delta N/\Delta \log dp$ at 7μm in Figure 5-1, denoted by $\propto$, is the same for each distribution. However, the total number of particles in each of the distributions (1-4) is significantly different.

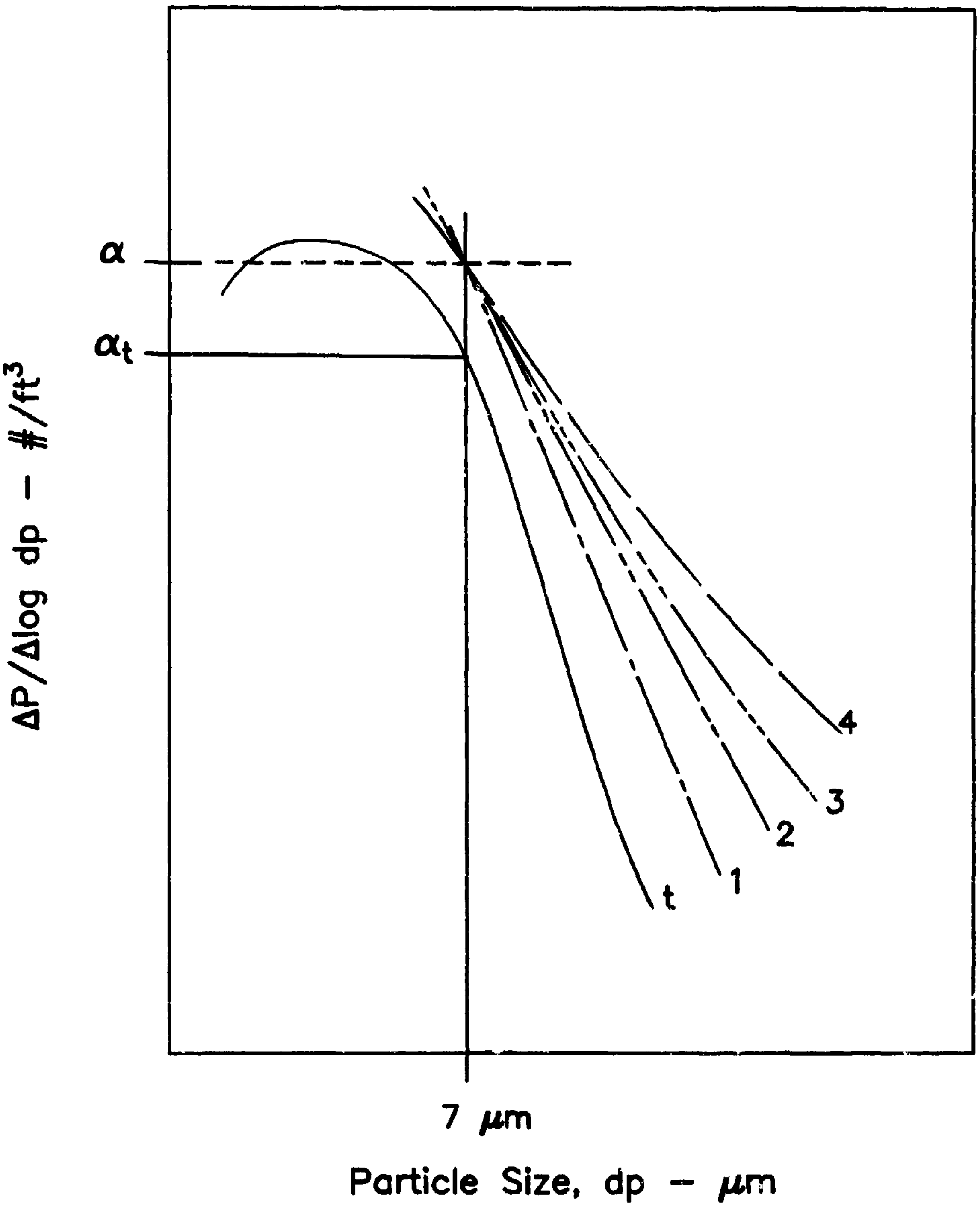


FIGURE 5-1. ILLUSTRATION OF INDEPENDENCE OF ΔN/ΔLOG DP, DENOTED BY ∝, FOR FOUR SPECIFIC DISTRIBUTIONS

The original values for particle size and concentration were set to be sufficiently outside a particular particle size distribution envelope to avoid false triggering when a new filter element (having lower efficiency than an in-service element) was installed, but to assure triggering when an abnormal (damaged, improperly installed, etc.) filter element was encountered. Major considerations were: 1) typical penetration distributions for new (inefficient) filter elements; 2) penetration distributions for damaged elements under typical dust conditions; 3) significantly damaged filters (for instance, elements with large leaks), but little dust; 4) time delay to ascertain whether the downstream dust was a singular event (such as a "blast" of dust after filter replacement caused by dust transferred to the clean air duct during handling) or a continuous trend indicating a failed filter; 5) sensitivity analysis of downstream particle concentration as a function of particle size to determine if sufficient discrimination existed to allow adequate thresholds to be developed; and 6) error bound requirements to allow for filter differentiation (by manufacturer, type, and vehicle) so a single detector could be used on all Army vehicles (a strong TACOM objective).

To examine potential criteria with respect to specifications and test data for military air cleaner systems, numerical data were converted to mass data so that the downstream distributions, as a function of mass, could be compared with the gravimetric (mass) analyses conducted during standardized filter testing. Calculating total mass penetration was accomplished by numerically integrating the area under the mass distribution curves for $\Delta M/\Delta \log dp$ versus dp, where

$$A = \Sigma_i \, (\Delta M/\Delta \log dp)_i \, (\Delta \log dp)_i \qquad (1)$$

Similar calculations were made for the numerical distribution data, yielding the total number of particles in a particular size range dp_1 to dp_2, or the total number of particles greater than a given size; for instance, 7μm, the particle size threshold. Another purpose for making the mass calculation from the numerical particle sizing data was to investigate and hopefully show a high degree of correlation between mass penetration, as calculated from the downstream particle size data, and penetration measured by weighing the downstream absolute filter after testing. As it turned out, these correlations were excellent, providing a high degree of confidence in the particle sizing data. Although the test particles were not spherical, sphericity was assumed in all calculations when converting from particle number to particle mass.

As already discussed, laboratory test data were used to quantify the downstream particle size distributions resulting from normal and abnormal (induced fault) 2½- and 5-ton truck

and M2/M3 air cleaner operation. These numerical distributions were then used to determine the concentration threshold in terms of the total number of particles per cubic foot greater than the size threshold of interest, which in this case, was 7μm. However, during the project, it was realized that the then current concentration value was likely an order of magnitude too high when stated without showing the accompanying particle size distribution. One reason was because the value taken from the particle size data, plotted as $\Delta N/\Delta \log dp$ vs dp, was not meaningful without integrating over a specific particle size interval. In fact, the number of particles having diameters exactly equal to a given particle size is zero because the interval width is zero.

The second reason was that changing the particle size threshold value from 5 to 7μm without changing the normalized concentration (threshold) value significantly altered the upper error bound and the margin of safety by greatly overstating the allowable concentration. In effect, this greatly increased the margin of safety against false triggering for a good system, but at the same time, greatly reduced the margin of safety for early detection of a faulty system.

As a result of the concentration controversy, a new analysis was conducted starting with a re-examination of the original test data. In this analysis, only data for the 5-ton truck and M2/M3 air cleaner systems was used since the 2½-ton truck was acknowledged to be of much less importance from a dust detector point-of-view. In addition, particular attention was focused on the error bound, the object being to avoid false triggering for the properly operating system, while still being able to trigger at the earliest possible warning of improper system operation. Finally, both the distribution curves and the discrete particle counting data were examined.

The database for normal and induced fault filter operation was constructed by counting downstream particles in six discrete size ranges as shown in Table 1. As such, the total number of downstream particles greater than 5μm could easily be determined for both normal and induced fault operation (while similar values for the 7μm case had to be interpolated). For instance, using the data on hand for the 5-ton and M2/M3 systems, and comparing maximum penetration values for new, properly operating systems to values for systems operating with induced faults, the degradation ratio for the total number of downstream particles (induced fault/normal) was on the order of 10-13 to 1, as shown in Table 2.

TABLE 1. HIAC 4102 PARTICLE SIZE ANALYZER COUNTING ARRANGEMENT DURING DEVELOPMENT OF DATABASE

Channel	Size Range, μm
1	0.5 - 1.5
2	1.5 - 3
3	3 - 5
4	5 - 10
5	10 - 15
6	>15

TABLE 2. CONCENTRATION OF DOWNSTREAM PARTICLE >5μm, FOR NORMAL AND INDUCED FAULT OPERATION, #/FT^3

Air Cleaner System	Normal Operation	w/Induced Faults	Degradation Ratio (induced/normal)
5-ton truck	9450	126500	13.4
M2/M3	28300	284140	10.0

At 5μm, the ratios of the normalized distribution values ($\Delta N/\Delta \log dp$) for the 5-ton induced to the 5-ton normal and the M2/M3 induced to the M2/M3 normal were 5.4 and 3.0, respectively.

To focus on the proper error bound, it was decided to work with the M2/M3 new element data and the 5-ton truck induced fault data because these data represented maximum and minimum penetration values for the (new) properly operating and induced fault elements, and therefore, provided the narrowest overall error bound, as can be seen in Figure 5-2. Ratios of the normalized distribution values for the 5-ton truck induced fault to those for the M2/M3 during normal operation at 5, 7, and 10μm were 2.4, 3.5, and 6.5, respectively. This meant that the distribution curve for maximum penetration under normal M2/M3 operation could be used as the baseline for investigating triggering threshold values that would avoid false triggering. At a 2:1 safety factor (+100%) with respect to this curve, the numerical concentration in the interval from 7 to 20μm (the full range of the data) was calculated as 77,500 particles per cubic foot air. However, a more careful review of the data showed that, in most cases, neither the new 5-ton truck or the new M2/M3 elements passed particles exceeding 10μm when operating normally. Therefore, since the intent is to detect abnormal operation as quickly as possible (without false triggering), only the narrow range of 7 to 10μm was used in the calculations. This produced numerical concentration values, for particles exceeding 7μm, of 18,000 to 24,000 with upper error limits set at 50 and 100 percent, respectively (Table 3).

TABLE 3. ERROR BAND ANALYSIS IN 7 TO 10μm PARTICLE SIZE RANGE FOR M2/M3 AIR CLEANER UNDER NORMAL SYSTEM OPERATION (EARLY ANALYSIS)

Upper Band Width, %	Safety Factor	Margin of Safety	Numerical Concentration, #/ft^3
100	2:1	1	24,000
50	1.5:1	.5	18,000
0	1:1	0	11,600

At this point (June 1989), a numerical concentration of 20,000 particles per cubic foot air (for particles exceeding 7μm) was recommended, a significant reduction from the initial specification.

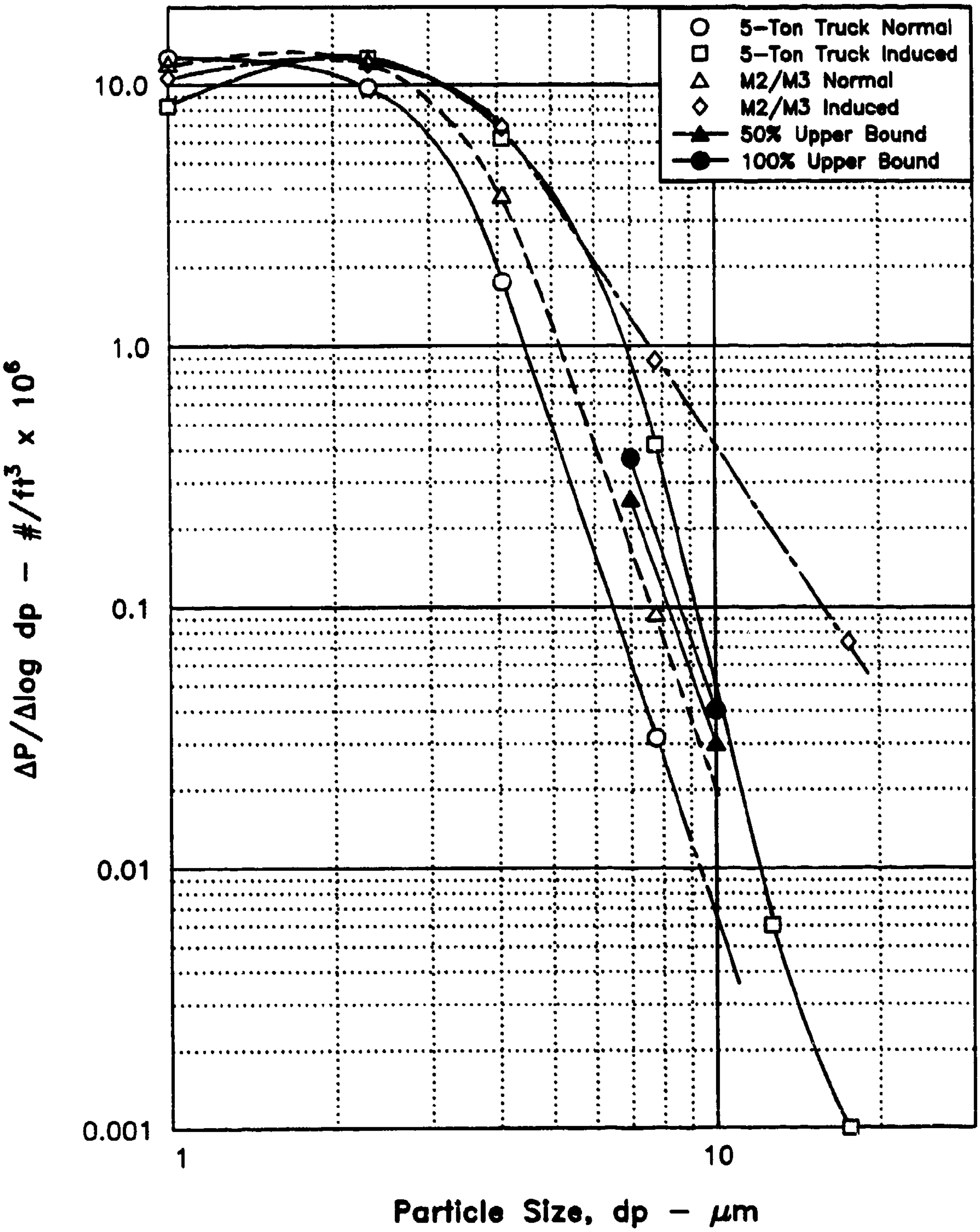


FIGURE 5-2. PARTICLE SIZE PENETRATION DATA FOR M2/M3 AND 5-TON TRUCK AIR CLEANERS, WITH ERROR BOUNDS FOR THRESHOLD CONSIDERATION

The concentration criterion was again considered later in the project as the result of another data review, which also included analyses of some second round and 5-ton truck full-scale test data. As a result of this review, both the concentration and response time criteria were altered to include some consideration of the specific technologies involved. Although perhaps not immediately obvious, this was necessary because different detector technologies respond to different particle properties, and therefore, a more general specification is required to avoid pre-selecting or prematurely precluding a given technology. This point will become more clear as development of these new criteria is reviewed.

At the outset, it seemed most appropriate to analyze the particle distribution data in terms of their differential concentrations, $\Delta N/\Delta \log dp$. However, this turned out to be less direct than using cumulative concentration, N, and in some cases, errors crept in when extrapolating the data to intermediate particle sizes. Overall, the data showed that the most dramatic differences between good filters and faulty filters occurred at particle sizes above $7\mu m$ when a reasonable error bound to protect against false triggering was taken into account. This meant that the dust detector needed to trigger when the concentration of particles $7\mu m$ or larger exceeded a certain threshold, which was previously calculated by numerical integration to be about 20,000 particles per cubic foot. This number turned out to be artificially high because uncertainties crept in when graphically integrating the estimated differential count densities. Furthermore, the end points for numerical integration were widely spaced, so that individual distributions, being approximately power-law, appeared as straight lines on log-log paper, and thus it was tempting to integrate using a single large triangle. When the original 5-ton truck and M2/M3 data were replotted on semi-log paper, it became clear that the power-law line was more steeply curved and must be divided more finely in order to integrate accurately, as shown in Figure 5-3. A better approach would have been to avoid the intermediate steps entirely (differential concentrations) and plot the raw cumulative count data (from the HIAC 4102 system) directly, as shown in Figure 5-4, particularly in the area of interest, above $3\mu m$. Particle data below $3\mu m$ were not particularly relevant because of over-concentration tendencies of the HIAC when very high concentrations of the smaller particles were present, and because particles in this size range made a relatively low contribution to the overall mass of particles in the airstream.

In Figure 5-4, the concentration of particles greater than $7\mu m$ can be interpolated directly from the line between the data points. Two curves are of interest: the curve for the 5-ton truck with induced faults, and the curve for the M2/M3 without induced faults. The reason is that the M2/M3 system represents the "dustiest" air through a good filter, while

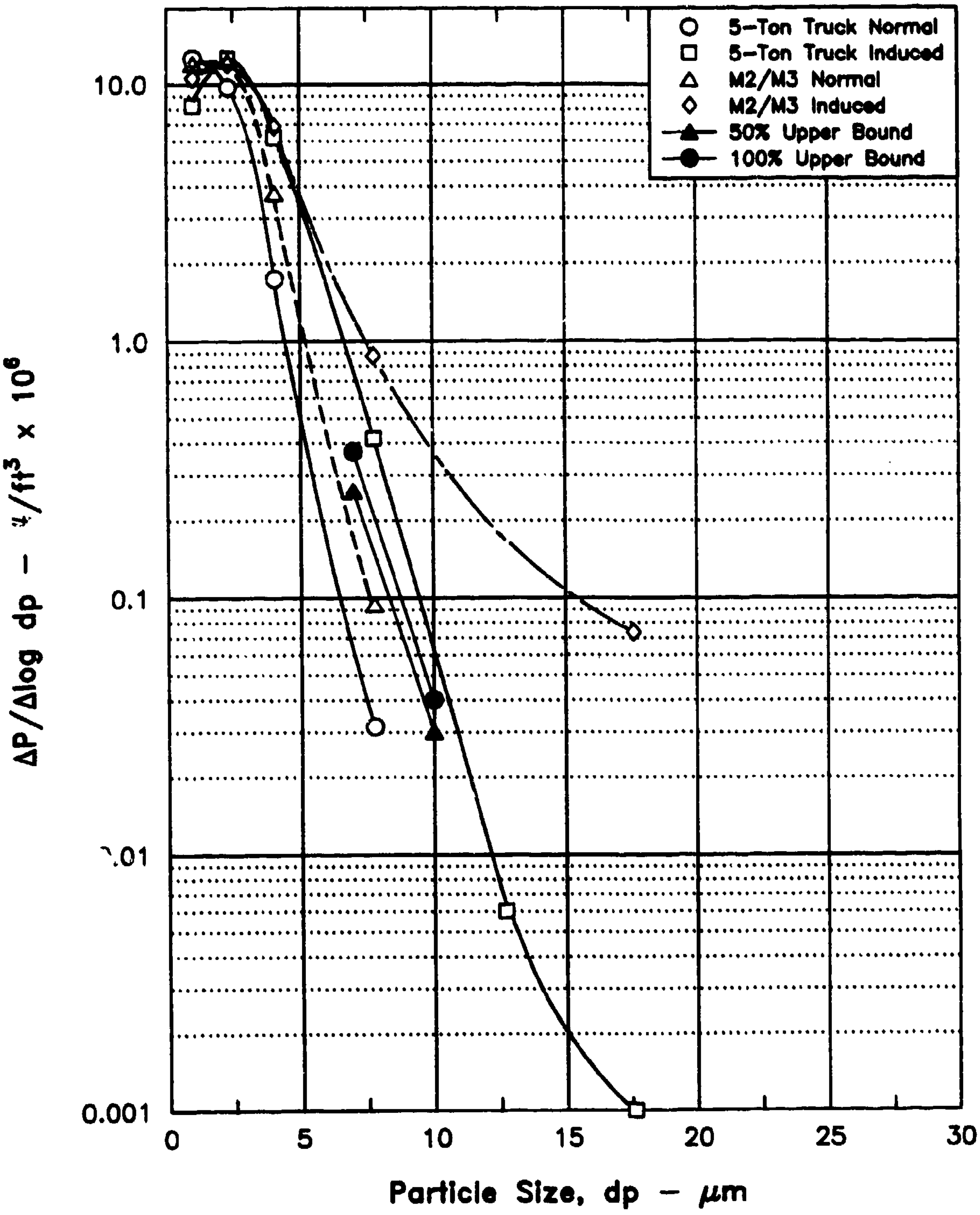


FIGURE 5-3. PARTICLE SIZE DATA FROM FIGURE 5-2 PLOTTED ON SEMI-LOG PAPER

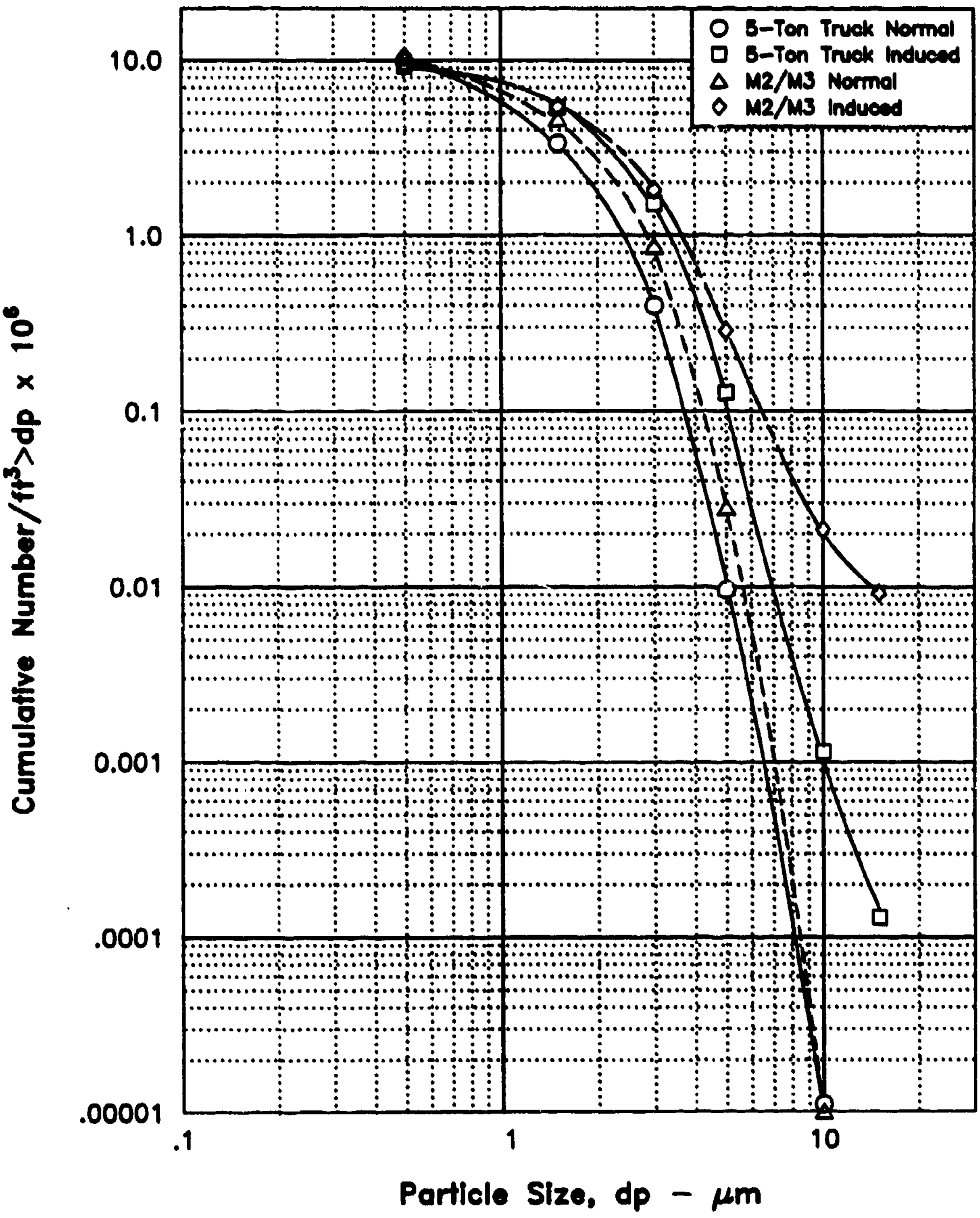


FIGURE 5-4. CUMULATIVE COUNT DATA FOR M2/M3 AND 5-TON TRUCK AIR CLEANERS UNDER NORMAL AND INDUCED FAULT OPERATION

the 5-ton truck induced fault case represents the "cleanest" air through a faulty filter, and therefore the area between these curves represents the zone which can contain the "go"/"no-go" criteria.

Developing these curves required extrapolation at the larger particle sizes. Differential and cumulative particle size data were available for the 5-ton truck induced fault case over the entire particle size range of interest. For the clean M2/M3 filter, however, there were generally zero counts greater than 10μm. In this case, one could conclude that the concentration was less than one 10μm particle per sample volume taken by the HIAC and to be conservative; that is, to be within the 98 percent confidence limit under Poisson assumption, one could further conclude, by considering the sampling arrangement (0.1 cfm sample flow with isokineticity), that there were fewer than ten particles over 10μm per cubic foot air for all M2/M3 "good-filter" conditions. Using the log-log representation for $\Delta N/\Delta \log dp$ and integrating the equation for the curve between 7μm and 10μm produced a concentration threshold of 3430 to 4015 particles per cubic foot air for this case.

Developing a specific "go"/"no-go" criteria leads to a triggering specification which lies between the "must trigger" and "must-not trigger" boundaries. The distribution for the dustiest air through a good filter defines the "must-not trigger" condition for the dust detector, whereas the distribution for the cleanest air through a faulty filter defines the "must trigger" condition. These curves then (reference Figure 5-4) can aid in determining the minimum functional requirements for the dust detector. In practice, it is advisable to provide a margin of safety for the "must-not trigger" curve in order to minimize the occurrence of false alarms. This methodology is the same as that used to develop the previous triggering criteria, except that cumulative data are now being used in place of the differential concentration data. This type of performance specification was developed at the suggestion and help of Chuck Harrison (HIAC/ROYCO) during a meeting at SwRI to review second round bench-test and 5-ton truck test data for the HIAC/ROYCO unit. As noted previously, the "must trigger" and "must-not trigger" conditions, based on 5-ton truck and M2/M3 filter performance, are the primary factors in defining the dust detector's functional requirements. Figure 5-5 shows a performance specification based on these data.

For the data shown, the edge of the "must-not trigger" zone is defined by applying a 2 to 1 safety margin on the measured performance of the M2/M3 filter, as was done in the previous analysis. All particle size distributions lying entirely under this curve must not trigger the dust detector. The edge of the "must trigger" zone is defined by a straight line

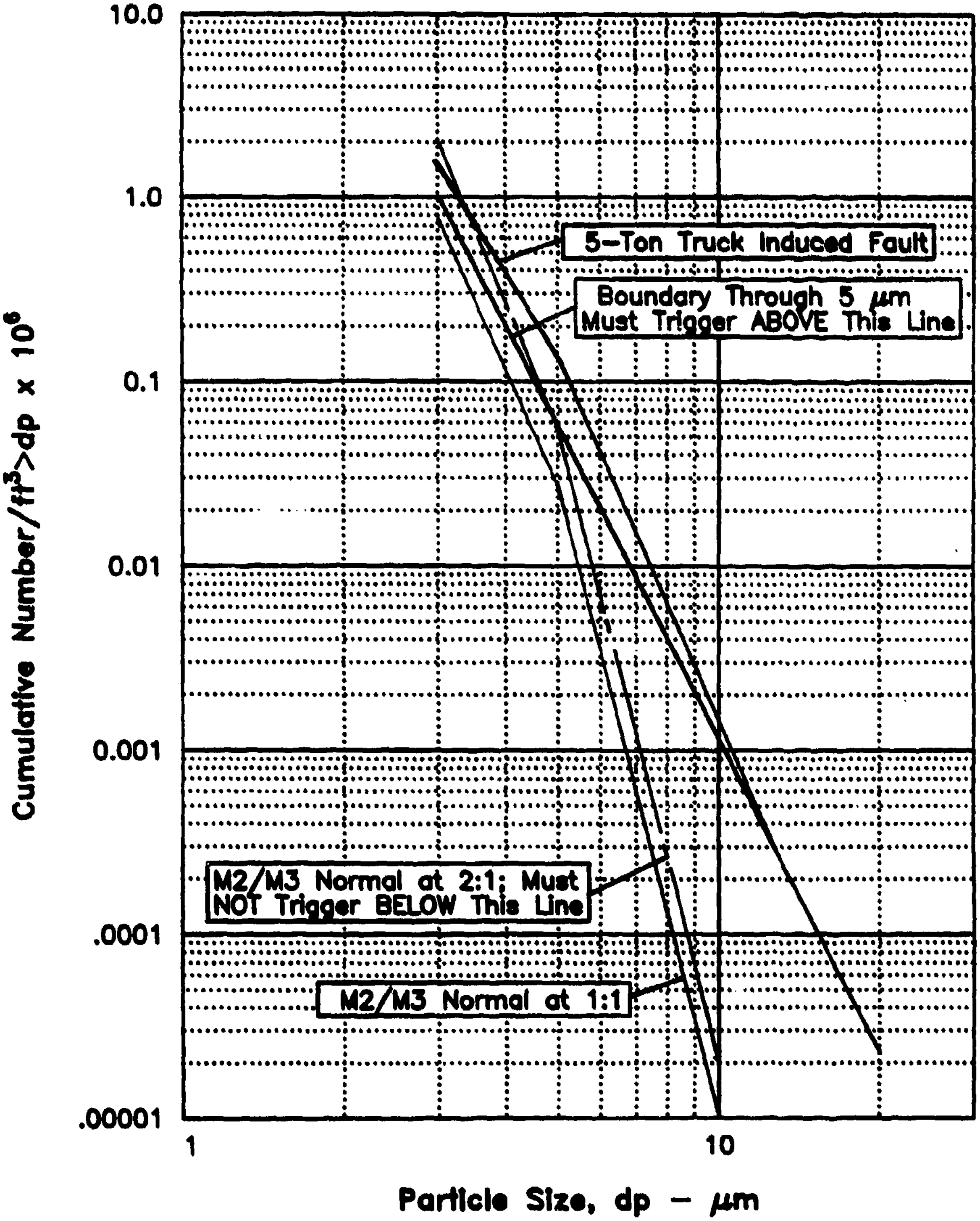


FIGURE 5-5. PERFORMANCE SPECIFICATION BASED ON "MUST TRIGGER"/"MUST-NOT TRIGGER" BOUNDARIES FOR M2/M3 NORMAL AND 5-TON TRUCK INDUCED FAULT DATA, WITH 2:1 SAFETY MARGIN AGAINST FALSE TRIGGERING

which lies under the measured performance points for a faulty 5-ton truck filter and passes through the 5μm point of the "must-not trigger" curve (the 5μm point is used because the "must trigger" and "must-not trigger" lines generally cross for particles below 5μm). Any particle size distribution line entirely above this curve must trigger the detector. Distributions which do not fall entirely within one region or the other are not representative of operating conditions (based on 5-ton truck and M2/M3 data), so the exact detector threshold is not important. Furthermore, the 5μm point assures that the detector will not respond to the presence of small particles which rather easily pass through the filter elements, particularly when the elements are first placed in service.

Interpretation of this specification is somewhat dependent upon the type of dust detector (sensor) being evaluated; that is, whether the dust detector responds to number or mass. An idealized sensor which responds directly to numerical concentration with a sharp diameter cut-off is particularly straightforward. For example, consider a sensor which responds directly to the number concentration of particles over 7μm. In this case, a concentration threshold setting anywhere between 1200 and 8500 particles per cubic foot would be acceptable, as shown in Figure 5-5. However, an idealized sensor which responds directly to mass concentration, with a sharp diameter cut-off, would respond somewhat differently. Figure 5-6 shows the distribution data from Figure 5-5 after conversion to mass units, assuming a nominal mass density of 2.6 grams per cubic centimeter and spherical dust particles. These data lead directly to a mass-concentration performance specification. For example, a mass-sensitive detector with a sensitivity cut-off of 7μm would require a threshold setting between .75 and 8.8μg of dust per cubic foot air.

During the course of the project, several sensors were evaluated for the dust detector application. Depending on the physical properties and implementations involved, the behavior of a sensor may show neither a perfect count response nor a perfect mass response, and furthermore, the sensor's size-sensitivity cut-off is not likely to be ideally shaped. Although these parameters affect the operating margin of the instrument; that is, the ratio between the minimum and maximum acceptable threshold, sensor performance can still be compared against a set of "must trigger" and "must-not trigger" distributions, such as those shown in Figures 5-5 and 5-6.

The problem posed by the foregoing discussion is one of setting meaningful triggering criteria without, at the same time, favoring a particular technology or specific method of approach. The solution is to specify a range of criteria for concentration and response time which, while somewhat technology dependent, are generally independent as far as the result is concerned. Thus, while several specific technologies might require and respond

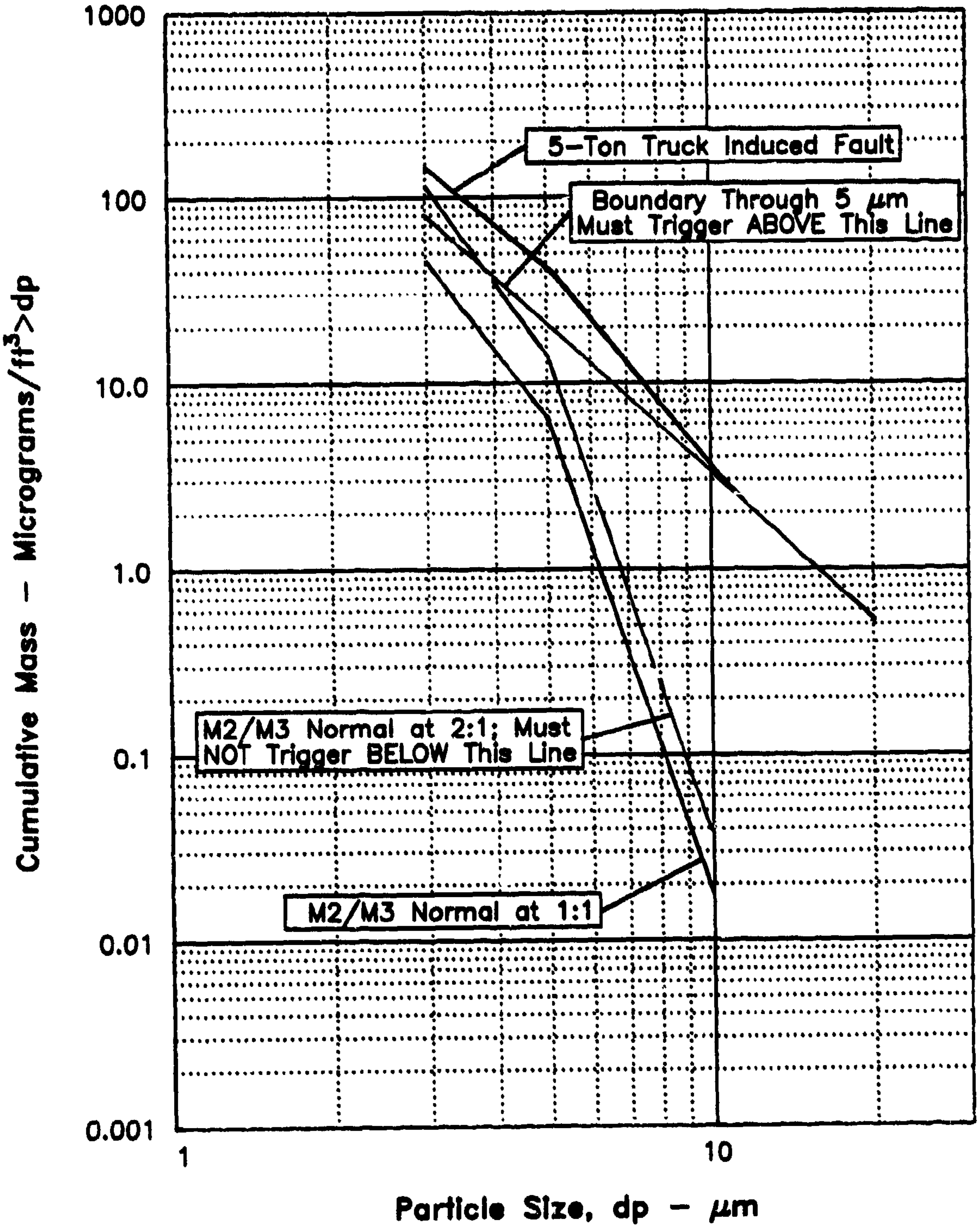


FIGURE 5-6. NUMERICAL CONCENTRATION DATA FROM FIGURE 5-5 CONVERTED TO MASS CONCENTRATION DATA TO DEFINE TRIGGERING ENVELOPE FOR MASS-SENSITIVE DETECTORS

to different criteria, the result; that is the triggering event, would be the same for a given dust distribution in that all of the detectors would either trigger or they would not, provided all were working properly. For the vehicles evaluated in this project (2½- and 5-ton truck, and M2/M3), the following triggering criteria were chosen:

Particle size	:	>7 μm
Numerical concentration	:	1200 particles per cu ft air
Mass concentration	:	0.75 μg per cu ft air
Response time	:	5 sec with false signal discrimination

5.2.1.1. Engine Wear. It was also intended that engine wear criteria would serve as a major factor in developing the dust detector specification. However, upon further analysis, engine wear criteria became much less important because:

1. The controlling factor, as far as dust ingestion into the engine is concerned, is the functional performance of the air filtration system, including operation under normal and abnormal dust environments with clean, dirty, and malfunctioning filters.

2. A dust detector built to respond to engine wear would be highly engine specific, and could vary considerably depending upon the engine technology involved. In fact, this type of criteria would require a myriad of specifications in order to treat all Army vehicles. Furthermore, engine age and condition would have to be taken into account, and sophisticated engine measurements would be required to assure that changes in engine wear or the presence of high engine wear were, in fact, attributable to a malfunctioning air filtration system.

3. While present air cleaner systems are designed to provide a reasonable (filter) service life and still give good engine protection under most operating conditions, this has required a trade-off between filter efficiency and filter service life that has led to specifications which inherently allow a large number of particles to penetrate the filter early in its dust loading history. Laboratory testing has clearly shown that both the amount and size of particles penetrating the filter decrease as the filter loads with dust, while fractional and overall efficiency increase. As a result, new (clean) air filter elements allow significant amounts of dust penetration, even under normal filter operation, even for filters that show high-average, or overall, laboratory

efficiencies. Furthermore, this dust remains in the engine much longer than if the dust were passed at the steady rate suggested by the average efficiency data. In addition, dust ingestion has an immediate and major effect on engine wear, and usually causes significant carryover wear even when dust is no longer being ingested. (Respecification of the filter element's initial efficiency requirements could help correct this problem, but would likely come at the expense of the filter's service life.) The tendency of a filter to pass large numbers of particles early in its loading history has already been discussed and has served as a major point of concern in developing the dust detector triggering criteria. There is no reason to believe that basing the criteria on engine wear would alleviate this problem. In fact, this would likely make it more difficult in the long run, since engine wear generally varies with more parameters than does filter dust penetration.

For these reasons, it was decided that the dust detector specification should be based primarily on particle size-concentration data, as discussed earlier.

5.2.1.2. Response Time. Some dust detector manufacturers argued that the response time requirement should be dependent on dust detector approach since response time is a function of sampler flow rate or the sample volume looked at by the dust detector. While there is no question that a strong relationship exists between sample flow and response time, as far as acquiring statistically significant sample is concerned, tying the response time requirement to a specific dust detector's sample flow rate misses the point. Instead, the dust detector must use a technology that can obtain the sample and make the necessary analyses, including the "go"/"no-go" calculation, within a sufficiently fast period of time to avoid large amounts of dust entering the engine in the case of a failed filter, while avoiding false triggering situations that can be caused, for example, by "particle burst" due to transient, and only transient events (such as might result immediately upon start-up after replacement of a used filter due to a dislodgement of dust which falls into the clean air side of the housing during filter replacement). For these reasons, the initial response time of one second was changed to five seconds, and under most conditions, this value seems reasonable.

It was also suggested that a "flexible" response time specification could help avoid false triggering for dust concentrations near the threshold level. For example, one might require triggering on 8500 particles per cubic foot within twenty seconds, while triggering on 20,000 particles per cubic foot within five seconds. This type of specification is possible for sensors which trigger based on concentration level and which respond immediately to high

particle concentrations, even if their internal integration process is not finished. With this type of sensor, the longer counting time provides good statistical information for discrimination near the threshold level, while responding rapidly to bursts of particles having concentrations that greatly exceed the threshold level. Although perhaps more unit-specific, this type of response time specification has considerable merit and should be considered, at least as an adjunct requirement.

5.2.2. Environmental Requirements. Dust detector requirements for operating temperature, shock and vibration, electromagnetic interference, and electrical interfacing are given in Table 4. Initially, the operating temperature for components normally installed in the engine compartment was set at 350°F. This was later relaxed to 300°F, which was considered more reasonable. This change was significant because of its impact on the technology. The 300°F temperature limit allows the use of many standard materials, many of which would be precluded at the 350°F requirement. This is a major factor in design and cost.

5.3. Candidate Detectors

Nine detectors were evaluated in this project, as shown in Table 5. Each of these units is described below, along with some discussion of first round testing, as appropriate. Results for second round and full-scale testing are presented later in the report.

It is noteworthy that each manufacturer, with exception of TSI, invested his own resources in completing modifications and developing his prototypes for testing. As pointed out earlier, no off-the-shelf units were identified that would meet the program requirements; however, certain designs and technologies were identified as having potential to be modified for this specific application. Most of the units tested were from manufacturers who were willing to make sufficient modifications to address the project's requirements in an effort to measure and hopefully demonstrate suitable functional performance. In addition, each unit was carefully analyzed beforehand to assess its potential for form, fit, and hardenability to meet rigorous on-vehicle environments. During the course of the project, significant advances were made in the state-of-the-art of particle counting technology, many directly applicable to the requirements of on-vehicle dust detectors. The most important of these are miniaturization, improved response, and the potential for hardenability to withstand sustained operation in harsh operating environments.

5.3.1. ATCOR. The ATCOR dust detector submitted for round one evaluation was a standard version of their portable, laser-based, 0.5μm airborne particle counter, with

TABLE 4. ENVIRONMENTAL REQUIREMENTS

Operating Temperature:

a. Components normally installed outside engine compartment — -25°F to 120°F

b. Components normally installed in the engine compartment — to 300°F

Shock and Vibration:

a. Basic Shock. Three 40 ± 4.0 accelerations due to gravity (g), 18 ± 0.02 milliseconds (ms) half sine wave shocks applied in each direction along the three mutually perpendicular axes, for a total of 18 shocks.

b. Gun Firing Shock. Three 55 ± 5.5 g, 2.5 ± 0.02 ms half sine wave shocks applied in each direction along the mutually perpendicular axes, for a total of 18 shocks.

c. Operational Shock. Three 55 ± 5.5 g, 0.5 ± 0.1 ms half sine wave shocks applied in each direction along the three mutually perpendicular axes, for a total of 18 shocks.

d. Non-Destructive Ballistic Shock. Shock impulses, as specified below, at the assembly mounting interface. Three shock impulses in each direction of the specified axis (six shocks per axis) shall be imposed.

Non-Destructive Ballistic Shock Conditions

Axis	Level	Duration
Latitudinal	200 ± 20 g	0.5 ± 0.1 ms
Vertical	200 ± 20 g	0.5 ± 0.1 ms
Longitudinal	550 ± 55 g	0.5 ± 0.1 ms

e. Vibration. Sinusoidal vibrations in each of the three mutually perpendicular axes at the frequencies and accelerations specified on the following page. Vibration frequencies shall be applied at a logarithmic sweep rate of 20 minutes per sweep cycle from 5 to 500 to 50 Hertz (Hz) followed by 20-minute dwells at each resonant frequency. Total vibration time, including dwells, shall be 120 minutes in each axis. Unless otherwise specified, the conditions of Specification MIL-STD-810D, Method 514.1 shall prevail.

TABLE 4. ENVIRONMENTAL REQUIREMENTS (Continued)

Vibration Levels

Axis	Frequency	Level
Vertical	5 to 25 Hz	1 g
	25 to 57 Hz	0.030 inch D.A.
	57 to 500 Hz	5 g
Lateral	5 to 25 Hz	1 g
and	25 to 44 Hz	0.030 inch D.A.
Longitudinal	44 to 500 Hz	3 g

Electromagnetic Interference (EMI):

Requirements per Part 4 of MIL-STD-461C and MIL-STD-462 [Class A3; ground facilities (fixed and mobile, including tracked and wheeled vehicles)].

a. Emissions:

CE03 - Conducted emissions, power and interconnecting leads, 0.015 to 50 MHz.

RE02 - Radiated emissions, electric field, 14 kHz to 10 GHz

b. Susceptibility:

CS06 - Conducted susceptibility, spikes, power leads

RS02 - Radiated susceptibility, magnetic and electric fields, spikes and power frequencies

RS03 - Radiated susceptibility, electric field, 14 kHz to 40 GHz

Electrical Interface: 24 Volts

TABLE 5. DUST DETECTORS EVALUATED

Name	Technology	Sensor/Duct Interface	First Round	Second Round	Full Scale
ATCOR	Forward light scattering	Sample withdrawn by probe and sent to sensor	X	X*	X*
AUBURN INT'L	Tribelectrification	Contact probe in flow stream	X		
EXTREL	Pyrolysis plus surface ionization	Contact probe in flow stream	X**		
MET-ONE	Forward light scattering	Sample withdrawn by probe and sent to sensor		X	X
MONITEK	Forward light scattering	Scans across flow stream	X		
MONITEK	Forward light scattering	Flow through probe containing sensor, inserted in duct		X	
HIAC/ ROYCO	Forward light scattering	Sample withdrawn by probe and sent to sensor	X		
HIAC/ ROYCO	Back light scattering	Window at duct surface, focal point in duct		X	X
TSI	Forward light scattering	Flow through probe containing sensor, inserted in duct	X		

* modified unit
** initial and modified unit tested

calibrated threshold settings of 0.5, 0.7, 1 and 5μm particles. A connector had been added to allow direct output of the signals to a pulse height analyzer. The sensor was designed primarily for cleaner room applications, sensing particles in the range of 0.5 to 5μm, in dilute concentrations. The detector is composed of three modules: the sensor, the pump/power supply, and the interconnect cable. The sensor module contains the measuring optics. Light emitted from a 10mw (at 780 nm) laser diode, which is contained within a closed assembly inside the sensor case, is focused by a series of lenses through a particle sensing zone into a light trap. When a particle enters the zone, it scatters the beam. Scattered light is collected by another set of lenses and focused onto a solid-state photodetector. The amplitude of the electrical signal produced by the photodetector is proportional to the size of the particle in the sensing zone.

During operation, a pump located in the pump/power supply draws sample air from the sample port through an orifice into the particle sensing zone. Filtered make-up air is also introduced into the sensing cavity to maintain the shape of the sample stream in the sensing zone and to prevent contamination of the cavity and transmission optics. Full optics protection is provided by a proprietary purge air and chamber design. The sensing optics and flow circuits are shown in Figure 5-7. Because the ATCOR unit was designed for clean room applications, it contained many functions not needed for an engine intake air dust (particle) detector. These functions, however, were useful in assessing instrument performance, and, in particular, the response to various dust distributions and dust concentration levels. Even though the ATCOR was not designed for vehicle applications, a review of its operation indicated sufficient potential to warrant first round testing. To handle the concentrations given in the initial specification, modifications would likely be

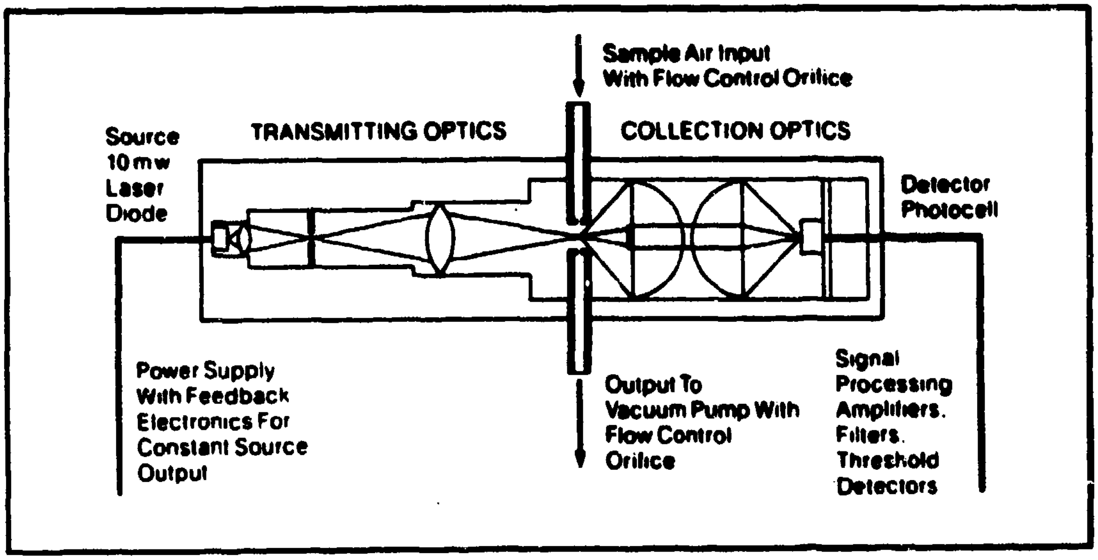


FIGURE 5-7. ATCOR SENSING OPTICS AND FLOW CIRCUIT

required to adjust the view volume, flow rate, and electronics with the objective of looking at larger particles at relatively high concentrations.

Because of its design sensitivity to measure 0.5μm particles, some variation between indicated counts and true counts was expected with this instrument. In its current design, the calculated maximum concentration for 5 percent coincidence was on the order of 2.8 x 10^6 particles per cubic foot air; thus, concentrations of small particles exceeding this rate would cause the indicated count to fall off with respect to the true count. Moreover, large concentrations of small particles could result in some of them being counted as larger particles if they agglomerate or spatially coincide in the sample volume. This would bias the indicated count for the larger diameter particles, making it higher than the true count. To prevent electronic ringing caused by the high gain circuitry needed to sense the smallest (0.5μm) particles, a program delay had been built into the count processing software. While of no consequence for clean room applications, this could cause the indicated count to be less than the true count by as much as 83 percent for very highly concentrated particle distributions. Nevertheless, it was decided to look at the instrument's response with respect to particle size and concentration level, understanding that specific design modifications could be made to alleviate sensing problems that might occur under conditions of high concentration. For instance, the requirement to sense at 0.5μm greatly complicates the electronics for the (current) instrument because below the wave length of the light source, the intensity of the scattered light is a function of the sixth power of particle diameter. Thus, the amplification circuitry must provide enough signal at 0.5μm, yet not saturate at well above 5μm. With the dust detector being required to sense particle in the range of 7μm and above, the electronic solution should be much less complicated, mostly a matter of detuning fine particle sensitivity.

Design changes could also be made to the sensor to compensate for the high concentration of small particles which will normally be present in the vehicle operating environment. For instance, the sensor could be redesigned, changing the view volume and flow rate to move the coincidence concentration higher. Conversely, it may prove more effective to simply remove the small particles before they reach the sensing zone. This could be accomplished by placing an inertial separator upstream of the dust detector, whereby the secondary flow

(containing the larger particles) would be introduced directly into the dust detector inlet. Should concentrations still prove to be too high, which is unlikely, an elutriation apparatus could be affixed to the inlet.

Because first round testing showed the ATCOR unit to have potential for sensing particles in the range of interest, the unit was returned to ATCOR for modification in preparation for second round evaluation. The primary modification concerned redesign of the sensor's inlet to increase detection sensitivity at the larger particle sizes. Although the read-out (0.5, 0.7, 1.0 and 5.0μm) was not changed because of time constraints, the unit was expected to provide more accurate distributions, which could be graphically extrapolated to 7μm and beyond. With the inlet modification, the instrument would be much more sensitive to larger particles, while minimizing coincidence and other errors caused by high, small particle concentrations. For example, ATCOR reported that the modified unit provided a 140 percent increase in detection efficiency at the 5.0μm level on particles of dispersed methylene blue and sodium chloride.

Since the ATCOR detector uses extractive sampling, the need to maintain near isokinetic sampling conditions, in the region of interest, in a highly fluctuating environment, was considered. If necessary, an electronic feedback loop between a flow stream sensor and the unit's vacuum supply could be used to adjust the sampling flow rate in order to provide a better match between the main stream and sample probe velocities. The sampling issue, for extractive samplers, has been discussed in detail elsewhere in this report.

To minimize particle settling and impaction losses within the system, it will be desirable to locate the sensor close to the sampling location, even though this may necessitate the use of thermoelectric cooling to maintain a safe operating environment for the laser diode. In fact, the entire sensor could be placed in a thermoelectric enclosure and ambient conditions could be monitored so that the enclosure could be adjusted to heat or cool the diode as required. The enclosure could also be designed to shield against spurious electronic signals.

At the time ATCOR submitted their prototype, they were also working on miniaturization of the electronics and optics to develop a small, lightweight, hand-held, battery-operated particle counter. A new prototype lens tube had been demonstrated and a preliminary design for a custom integrated circuit, which combines the electronics of several boards onto a single chip, was completed. If warranted, ATCOR intended to incorporate requirements of the inlet dust detector into this chip.

5.3.2. AUBURN INTERNATIONAL. The dust detector submitted by AUBURN INTERNATIONAL is based on the triboelectric effect and is an offshoot of instruments AUBURN markets to monitor the flow of dry solids in many different applications. Auburn International stated that their unit can be used for almost all materials and is suitable for use with particles of sizes varying from a few centimeters down to 1μm. They noted that a major use for their probe is in monitoring bag house fabric filter failures, particulate carryover, and particle flow failures. In operation, the probe is inserted in the flow stream and the continual transfer of charge taking place as each particle impinges on the probe results in the generation of a triboelectric current, which is dependent on and proportional to the flow conditions. The triboelectric effect and triboelectric technology are explained in detail in references 2, 3, and 4.

Triboelectrification results when the transfer of charge takes place as two materials collide or are rubbed together. In this application, the friction of the particles passing over the metal probe transfers a measurable charge from the moving particle to the probe surface. This allows the instrument to directly detect a loss or onset of particulate motion, depending on the reference condition. Furthermore, experiments have shown that the current developed is proportional to the particle velocity and mass flow rate, and inversely proportional to particle size. A system based on the triboelectric effect electronically amplifies, processes, and compares this signal with a desired preset norm, and any significant deviation can be used to trigger an alarm.

Preliminary test of the AUBURN detector were run with mixed results. While the instrument initially showed sensitivity to several of the dust distributions introduced to it, sensitivity decreased over time as the probe became coated with a thin layer of dust. Furthermore, some difficulty was encountered in adjusting sensitivity to various dust distributions (particle size and concentration levels). This was not overly surprising since this was a "look-see" type test to examine the instrument's potential for adaptation to a new, more complex application. Although not highly quantitative, the data indicated that the AUBURN device could be made to trigger in the range of interest, provided the sensitivity problem could be solved. AUBURN felt they could add control parameters that would adjust to the dust build-up (auto-zeroing), and change (increase) impedance to make the probe less sensitive to the (small particle) background. They also stated that an improved microprocessor was being developed, which would change somewhat how the measurement is computed. The unit was returned to AUBURN for modification; however, after further consideration, AUBURN decided not to continue in the program. Accordingly, no further tests were conducted on the AUBURN prototype detector.

5.3.3. EXTREL. The theory of operation for the EXTREL probe is discussed in detail in Reference 5. In summary, the prototype dust detector used a pyrolysis plus surface ionization (PPSI) technique which operates somewhat as follows. The sensor is a heated (925°C) platinum surface on a diesel engine glow plug. Dust particles striking the surface transfer some of their surface-ionization constituents (usually sodium compound impurities) to the surface. The sodium is surface-ionized and arrival of a particle is marked by a short burst of many sodium ion which are drawn to an adjacent ion collector, creating an electrical pulse which is processed by circuitry while another particle approaches the surface.

Surface ionization is a process wherein an electrically neutral atom or molecule with a low ionization potential strikes a metal surface with a high work function and transfers an electron from the atom or molecule to the surface. The atom or molecule then leaves the surface as a positively charged ion. Heating the surface to maintain an elevated temperature increases the probability that surface ionization will occur from atoms with ionization potentials comparable to or greater than the work function of the surface. Heating also speeds up the evolution of the ions from the surface. In addition, when working with biological molecules, Myers and Fite realized that high surface temperatures would pyrolize complex molecules, breaking them into their constituent atoms and radicals, and when working with dust and smokes (because of their simplicity) they found that pyrolysis-plus-surface-ionization proved to be an extremely sensitive method for detecting almost every type of dust or smoke particle.

Myers and Fite also realized that the vast majority of ions produced in ordinary dust and smokes were sodium atomic ions (Na^+) and that sodium compounds are present as impurities (in virtually everything) at sufficiently high concentrations that large electrical pulses could be produced. For example, a typical, 1μm, coal dust particle will produce on the order of ten million ions. While most particles are not completely pyrolized into gaseous constituents at the surface (particle size is a factor), enough transfer of surface ionizable constituents takes place to record the arrival of the particle.

Work to monitor ambient air and air in stacks and ducts led to development of a surface ionization probe based on a hot surface in the form of a hot filament of platinum or platinum-alloy wire. In a conventional SIMP (surface ionization monitor for particulate) sensor, the filament is heated resistively and biassed at a high positive potential (of a few hundred volts). This requires heating the filament to the 800-1400°C range, and while this causes good surface ionization, it also causes the diameter of the filament to decrease with time, as some of the surface is evaporated away. To compensate, a brightness regulation

technique was used to maintain the filament temperature relatively constant over long operating periods (months). The ion collector is connected to the input of the SIMP electronics and is maintained near ground potential, which permits measuring the time-integrated positive ion currents, as well as counting and sizing the individual pulses.

In a glow-plug SIMP, the device chosen for the automotive application, the active platinum surface is placed on the glow-plug itself and the plug is indirectly heated by a Joule heating element inside the surface. Because of its mass, the glow-plug's temperature is independent of the amount of platinum present; hence brightness regulation circuitry is not required. However, the hot surface is now at ground potential and the ion collector must be biased at a high negative voltage. It was recognized that some control over glow-plug temperature would likely will be required when using the glow-plug SIMP in the intended vehicle application. This is because air velocity and changes in air velocity in response to changes in vehicle operation will affect the rate of cooling of the sensor as a function of time.

The EXTREL probe was tested early in the program with mixed results, although further testing showed the probe to be unsuitable as a long-term automotive dust detector because of probe desensitization under long-term exposure to fine dust particles. Before describing the test results, it is first important to describe how the tests were conducted. This is necessary because the EXTREL probe was in its early stages of development, and therefore, the initial tests were very exploratory in nature. In fact, the initial testing was somewhat of a cooperative effort with EXTREL personnel in attendance. Since the purpose of these earlier tests was to "tweak-in" the instrument in order to evaluate its potential as a vehicle dust monitor, adjustments were made to the instrument from time-to-time during testing.

For the most part, testing concentrated on measuring the sensor's functional response; that is, its ability to respond to specific dust distributions of varying particle sizes and concentration levels which simulated many of the dust environments typically admitted to engines during normal and abnormal filter operation. The standard test arrangement, as described in Paragraph 5.5.2.4 was used, and in effect, two distinct series of tests were conducted. As noted, in the first series of tests, the standard or initial probe was "tweaked-in" and evaluated. Prior to the second series of tests, the probe was modified by EXTREL to include a pre-impactor, which was intended to reduce fouling by preventing the impaction of particles whose sizes were outside the range of interest.

During testing, the criteria of particular interest were the indicated triggering points as a function of particle size and concentration, and the probe's stability and sensitivity in prolonged dusty environments. The ability to set and maintain a sharp difference in response to distribution passing above and below the triggering point would indicate good potential for "go/"no-go" operation within the immediate range of concern. A "go"/"no-go" response to particles within some other range would not necessarily be detrimental at this point because the test actually represented the first exposure of the sensor (and its technology) to the specific dust distributions of interest, and therefore, a need for adjustment (or even modification and refinement) was to be expected. Of course, failure to provide a discriminable response to various distributions in a range of say 1-15μm would be cause for concern.

It is noteworthy that the instrument's characteristics were measured in response to an assemblege of "road dust" particles rather than to challenge by a nearly monodispersed distribution or spherical particles of a single size. As a practical concern, the dust streams present in military vehicle intake systems will generally be an assemblage of particles with sizes that can easily range over two or so decades in magnitude. Furthermore, according to previous experiments which measured the penetration characteristics of normal and abnormal filters, the downstream distributions of concern are likely to be highly skewed inversely to particle size. As a result, it is the response to continuous distributions that is important rather than the cumulative response of several individual tests using monodispersed (laboratory) particles, which are often taken collectively to show the instrument's expected response over a particle size range. Obviously, this later type of test does not consider the response when polydispersed, non-ideal particles are encountered simultaneously.

The sensor's response as a function of concentration level was determined by looking at the overall response of the instrument for given sets of dust distribution and operating conditions. This showed that the sensor, when clean, was responsive (or sensitive) to concentration level; however, it did not necessarily mean that the particular response represented a discrete concentration level that would be independent of flow conditions. The sensor's method for measuring concentration and the accuracy of the concentration measurement were of concern because the triggering criteria was based on both concentration and particle size. It was quite likely that the EXTREL sensor would also have to measure air flow so a true concentration could be determined.

Because numerous adjustments were made during the test period (for instance, discriminator setting), comparison of individual test runs required careful consideration. Nevertheless, certain trends were identified, providing a fairly good indication of overall instrument response and potential. Overall, these trends showed decreasing instrument response with increased dust loading on the probe, with several tests implying drift or instability even during a single test run. The probe was also plagued by baseline drift, likely caused by some electronic problem in the power supply or due to a shorted connection, or ground loop phenomena.

As mentioned earlier, the second criteria of interest was stability, particularly with regard to the probe's longer-term exposure to "dusty" environments. During actual operation in military vehicles, the probe will be exposed to dust in at least two ways. Under normal filtration conditions, the probe would very likely be exposed to large quantities of very fine dust over long periods of time, a condition that could easily cause fouling as the probe becomes coated with dust. Changes in response or sensitivity as dust builds on the probe could indicate a significant problem regarding the long-term stability required for unattended operation. Under abnormal filter operation, which is the condition the probe is intended to detect, relatively large amounts of "coarser dust" would likely impact the probe over a very short period of time. In this case, the detector would be expected to trigger a warning, and once this is done, the detector will be considered to have done its job. It would be nice, however, if the detector could also be put back on-line without requiring major maintenance on the probe. Whether or not this becomes a requirement will likely depend on the difficulty associated with the maintenance function, and perhaps with the cost involved. For instance, the probe may be such that it is removed, cleaned, reinstalled, and reset, or it could be a throw-away item which is simply replaced.

Considering the response and stability criteria for the test conditions investigated, it was concluded that the EXTREL probe showed short-term responsiveness to dust distributions that were in the general area of interest, but that its long-term stability and responsiveness decreased with increasing dust exposure. Long-term exposure to smaller particles intensified this effect. Probe stability was sensitive to input voltage and filament temperature. The probe was also found to be responsive to air flow rate, independent of dust concentration, with the probe's discriminator setting greatly influencing the overall response of the instrument. For instance, for a discriminator setting of 1 (in arbitrary units), the probe responded to changes in air flow rate for stream conditions showing little or no appreciable dust. For discriminator settings of 2 and above, the probe was insensitive to changes in air flow rate. Prior to fouling, probe sensitivity to changes in particle

size and concentration level was dependent on the discriminator setting. At low discriminator settings, the probe responded to changes within seconds.

The ability of the pre-impactor to reduce fouling was marginal and there was some question as to whether the approach taken was appropriate for attacking the fouling problem. Testing had shown that exposure to the smaller particles seemed to intensify the fouling problem; however, these particles were least effected by the impactor design employed. It was clear that considerable refinement would be necessary to obtain a satisfactory unit for military vehicle application. As a result, it was recommended that:

1. Primary attention be directed towards solving the probe fouling problem. Methods to reduce impaction of the smaller particles (say, below 5μm) might be warranted. In this regard, consideration could be given to air sheathing, filament design to reduce particle capture, and "washing" or regeneration methods, including filament temperature control. The influence of discriminator setting could also be considered as a control technique.

2. Long-term testing should be accomplished when addressing the fouling problem.

3. Sensor response as a function of discriminator setting should be better defined so that a "go"/"no-go" response could be obtained at or near the required threshold level. Further bench testing should be conducted in this regard.

4. Mechanical improvements should be made to assure probe structural integrity during bench testing. Ultimately, structural integrity must be sufficient to allow vehicle operation.

5. Once improvements were made and demonstrated, longer-term testing on a full-scale simulator (for example, a 2½ or 5-ton truck air cleaner assembly) under normal and abnormal filter operation should be accomplished.

In their analysis of the test results, some concern was raised by EXTREL that the fouling which led to a loss of sensitivity was predominately caused by large particles (because some AC Coarse Dust was used during testing), and that ducting to the HIAC could have resulted in transport losses which would have negatively influenced the results (by ignoring the larger particles, say greater than 10μm). Because of these concerns, the test method

and procedures, the test results, and the method of operation of the EXTREL unit were carefully reviewed. While details of this review are presented in Appendix A, including suggestions for improving probe operation, it was concluded that the test was conducted properly and that the results obtained accurately represented how the EXTREL probe would perform on a vehicle, over time, under normal filter operation. In particular, it was found that the EXTREL probe would capture a large number of small particles, which would eventually foul the sensor. Secondly, more than 50 percent of the particles at or above the 7μm threshold would be "invisible" to the EXTREL probe because they would pass without impacting the sensor. Finally, the pre-impactor, as currently configured, would not reduce the fouling problem, and instead, would actually diminish the suitability of the probe. Consequently, the EXTREL probe was considered functionally unsuitable for its intended application. As a result, the EXTREL probe was eventually dropped from the test program based on the bench test results, primarily because of probe instability and the failure of EXTREL to properly address the instability/fouling problem.

The EXTREL (and AUBURN) experience underscores the major problem with insertion-type probes. Over time, these probes are eventually desensitized by the continual stream of small particles which collect on their surfaces and often agglomerate to form a "barrier" that prevents the probe from detecting further particle impacts. As a result, these probes were judged to be inappropriate for the application at hand.

5.3.4. MET-ONE. The MET-ONE detector was added late to the program (because it appeared to have reasonable potential) and was therefore only subjected to second round and full-scale testing. MET-ONE originally initiated an effort to supply a prototype dust detector in accordance with our general correspondence of 1987, but did not follow through because they decided an appropriate product would require excessive modifications to meet even the minimal requirements of our program. Later, however, MET-ONE developed a product for the commercial market which appeared, in many respects, to be suitable for the military application. This new product, called a burst detector, was a small, simplified, solid-state particle counter which could detect increases in particle quantity, and initiate a simplified signal, such as a switch closure or panel light.

Due to its small size and simple construction, the burst detector appeared useable in military applications. Furthermore, a demonstration prototype was available for testing. As such, the prototype was obtained, and after further review with MET-ONE concerning its operation, it was decided to include it in second round testing, and, if appropriate, in the full-scale 5-ton truck test. Figure 5-8 shows the MET-ONE detector during second-

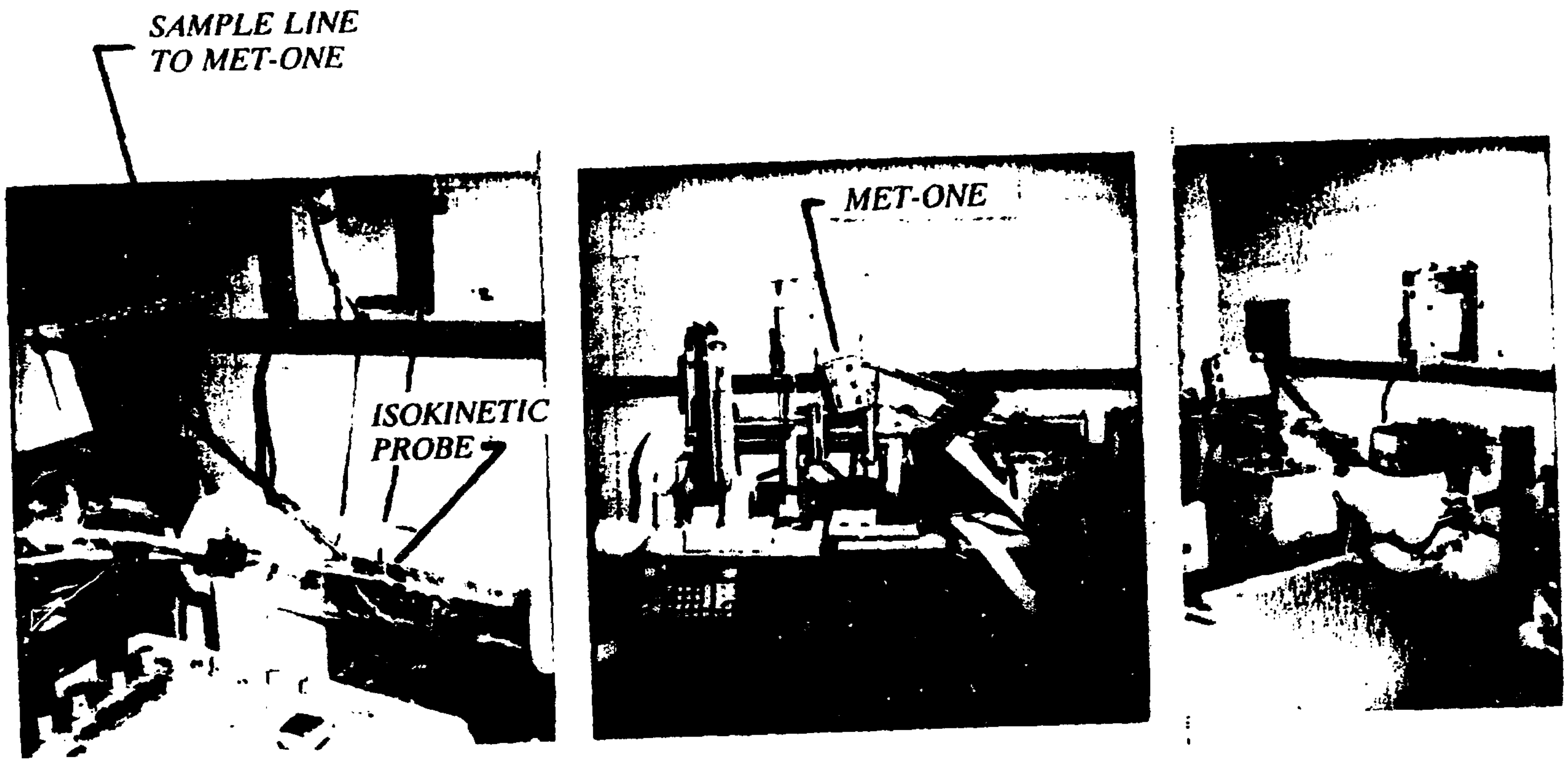


FIGURE 5-8. MET-ONE PROTOTYPE DURING BENCH TESTING

round testing, while Figure 5-9 shows the unit during the full-scale 5-ton truck laboratory test.

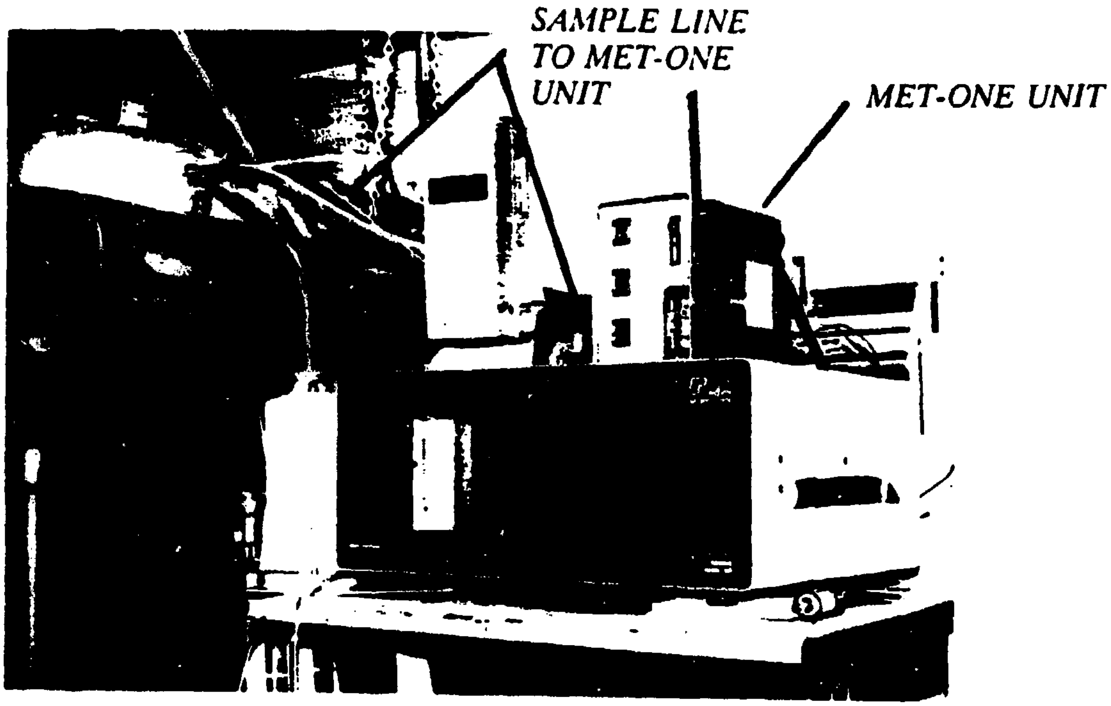


FIGURE 5-9. MET-ONE PROTOTYPE DURING FULL-SCALE 5-TON TRUCK LABORATORY TESTING

The MET-ONE unit tested was a modified burst detector intended to provide continuous monitoring of engine intake air quality. The unit operated by extracting a sample from the flow stream and transporting it to a remote sensor for analysis, The sole output was a triggering signal such that an alarm would sound and an LED light would go on when the burst detector's sensor measured more than a certain number of particles (supposedly 7μm and larger) for longer than a specified number of seconds. Particle concentration limits could be set at 50,000, 100,000, 250,000, and 500,000 particles per cubic foot air, and the delay time could be set at 1, 2, 5, and 10 seconds.

During operation, flow through the sensor was held constant in order to maintain calibration. MET-ONE reasoned that, although the flow past the sample probe within the intake duct may have wide fluctuations, a constant (0.1 cfm) flow through the sensor would serve to deliver data that relates to a known volume or concentration. As discussed earlier, this arrangement is not adequate for a vehicle dust detector because it does not provide a measure of true concentration for the particles dispersed in the duct.

Operation of the MET-ONE sensor can be summarized as follows. The detector's laser diode creates a beam that is used to detect particles. When airborne particles pass through the laser beam, light is scattered onto a solid-state photo diode that converts the light to electrical pulses, whose amplitude is related to particle size. The associated circuitry counts these pulses and sets an alarm latch as needed, as shown in the diagram in Figure 5-10. The prototype dust detector was calibrated using polystyrene latex spheres. The 7μm threshold was obtained by setting a voltage using a variable resistor potentiometer and both the count limit and delay time were switch-selectable.

MET-ONE has made significant progress in reducing the size of the particle detector. However, the same drawbacks noted in the previous unit remain; in particular, constant flowrate sampling without correlation to the in-duct flow. Test results from second round and the full-scale tests are given in Paragraph 5.4.4.2.

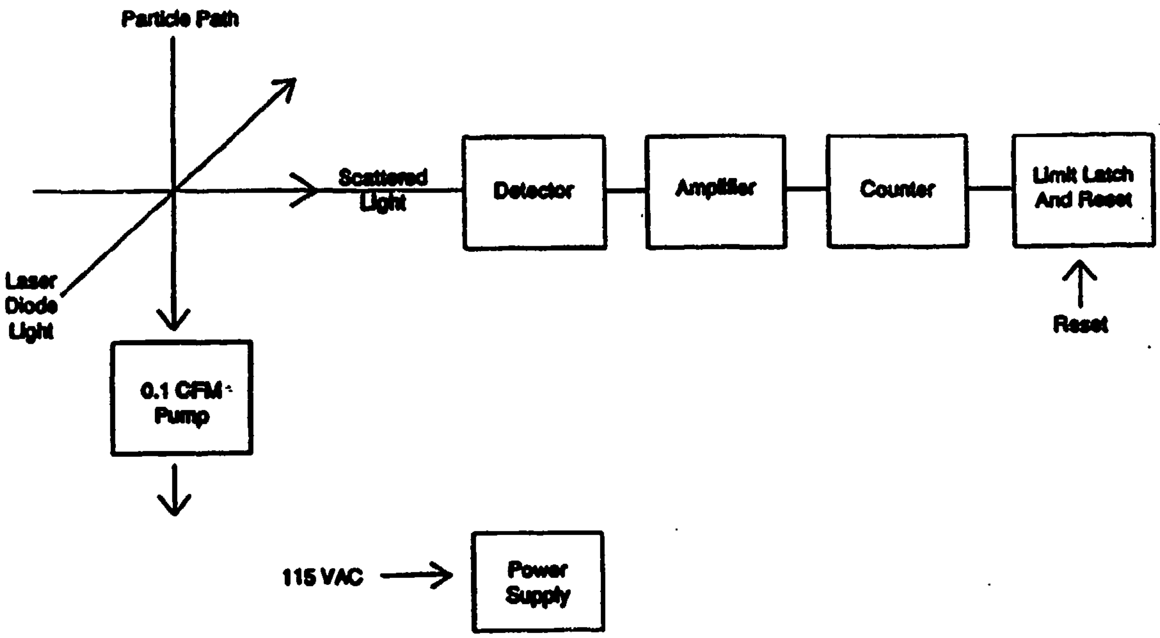


FIGURE 5-10. MET-ONE CIRCUITRY BLOCK DIAGRAM

5.3.5. MONITEK. The MONITEK instrument submitted for round one evaluation was primarily designed for petrochemical (liquid) applications. Nonetheless, this unit was included in the test program because of its rugged construction and because an analyses of the technology indicated good potential for our application. This unit is shown under test in Figure 5-11. The actual unit tested was a Model 210 turbidimeter consisting of two main parts: a model 210 sensor, which is installed in the process stream, and a Model 130 indicating transmitter, which consists of the meter and electronics package. While the Model 130 indicating transmitter has been used in a variety of industrial applications, it has been found to be especially popular in monitoring liquid filtration processes and in process quality control.

The 210 sensor is a rugged in-line sensor which measures "turbidity" by ratioing the signal from the forward scattered light beam to the signal of the direct light beam. The term "turbidity" is often associated with liquids, although it is actually the term given to the attenuation coefficient which relates the intensity of a beam emerging at a distance ℓ to the intensity of the beam incident on a dispersion of Rayleigh scatterers(6), hence turbidity represents the total energy scattered by a unit volume of scattering material for unit incident intensity, or stated differently, the amount of light scattered is related to the concentration of solids present. Turbidity, then, is truly an optical property (of the fluid) and is related to the presence, nature, and concentration of discrete aggregations of material which differ from the pure fluid carrier. In many practical applications, turbidity is often considered (and defined) as an appearance parameter and thus can only be measured by optical techniques.

It is generally not possible to deduce absolute mass concentration levels in a liquid sample from turbidity measurements alone, since the degree of turbidity is strongly dependent on the size, shape, and color of the particles; the host fluid refractive index; the wavelength of the observation light; and the viewing geometries. Turbidity measurements are only proportional to mass concentration if all of these parameters are held constant. Nevertheless, the signals produced by a turbidity meter are quite sensitive to particle size and number, and therefore, after examining the manufacturer's data showing instrument response under various situations, it was decided that the technology being employed might have direct application to the dust detector project.

As already noted, one of the major applications for the Model 210 turbidimeter is the detection of filter breakthrough. In fact, this instrument has been particularly successful because its forward scattering technique allows the sensor to distinguish between

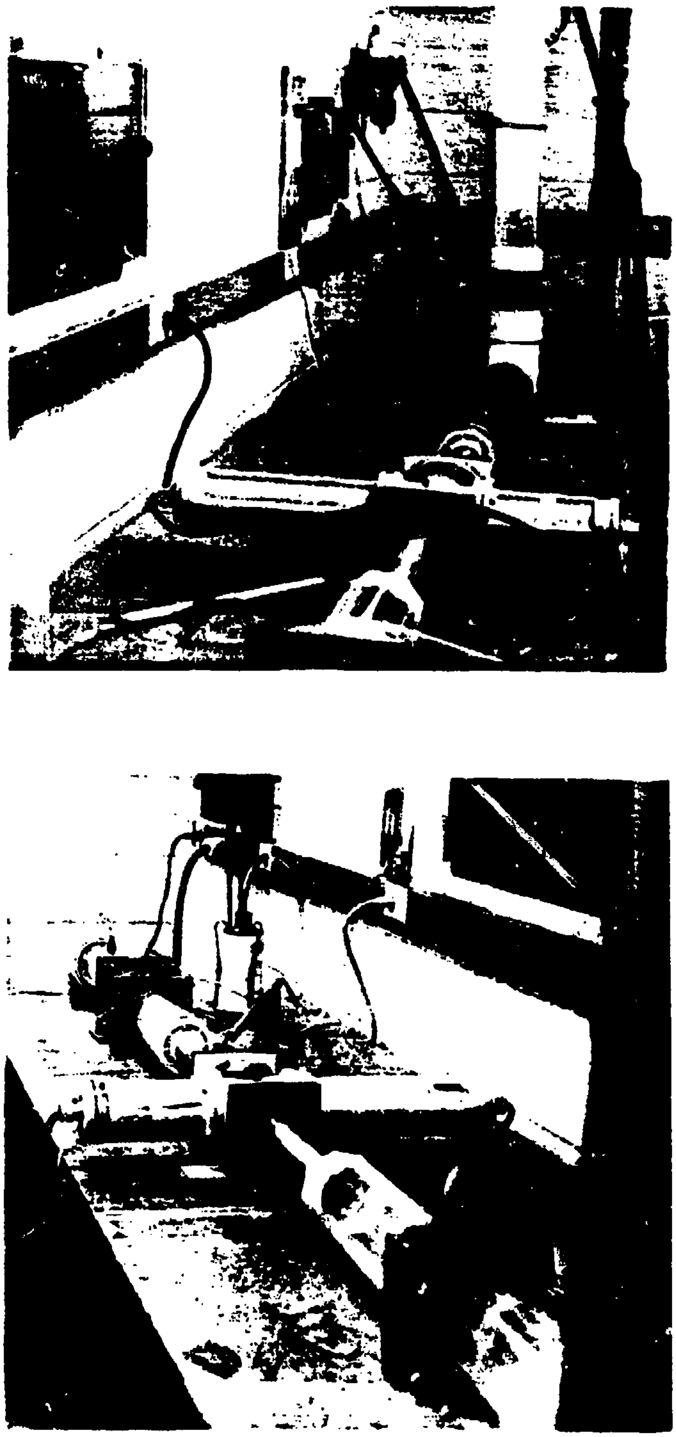


FIGURE 5-11. INITIAL MONITEK UNIT UNDER TEST
(Also See Figure 5-33)

background haze (non-filterable) and the breakthrough of filterable particles. (Suspended solids in a flow stream will scatter light in all directions; therefore, there are many potential angles for viewing the scattered light.) The unit tested in this program used the forward scattering technique because it provided improved sensitivity, and because it sampled a more representative cross-section of the process stream, and thus could monitor a wide range of particle sizes from 0.1 to 100μm. Spatial filtering (a MONITEK patented design) was employed to prevent light scattered from the surfaces of glass windows from affecting the reading. This feature consists of a series of baffles and light traps in the detector assembly (Ref. Figure 5-12).

As mentioned, both the scattered light and the direct beam light transmitted through the sample are measured. The scattered light signal is then divided by the direct beam signal. This ratioing approach gives the following benefits: first, the instrument has a known zero because no light is scattered when particles are not present; second, the instrument is not sensitive to liquid and particle color changes because the scattered light and direct beam are equally affected; third, readings are not affected by light source intensity changes, by line voltage fluctuations, or process temperature variations; and finally, the instrument is linear over a specified range.

Figure 5-12 schematically shows the operation of the in-line, forward-scatter turbidimeter. The light source (a) generates, by means of an optical component, a thin ribbon of light (b) crossing the product stream (c). The use of several apertures in the projection optics gives this ribbon a sharply defined edge, eliminating the problem of stray light from the source section. After transversing the product stream, this ribbon of light is intercepted by a direct beam detector (d), which is designed so that no light is scattered from its surface back to the source. Light scattered in the forward direction by particles in the stream (e) passes to each side of this detector where it is focused by the condensing lenses (f) onto the scattered signal detector (g). Both detectors are photo-current generators and are accurately linear with incident light intensity. The two signals are amplified and their ratio is computed. This ratio is the basis for the output signal and is proportional to the total forward scattering cross-section of particles in the stream, up to levels of several thousand parts per million (for distomaceous earth in water; PPM D.E). This type of detector also generates zero signal when in the dark, so that the linearity of the output ratio with turbidity is maintained down to the low part per billion (PPB) range. For particles which are equal to or larger than the viewing wavelength (greater than 0.5μm for visible light), forward scattering is at least 100 times as intense as the perpendicular or back scattering.

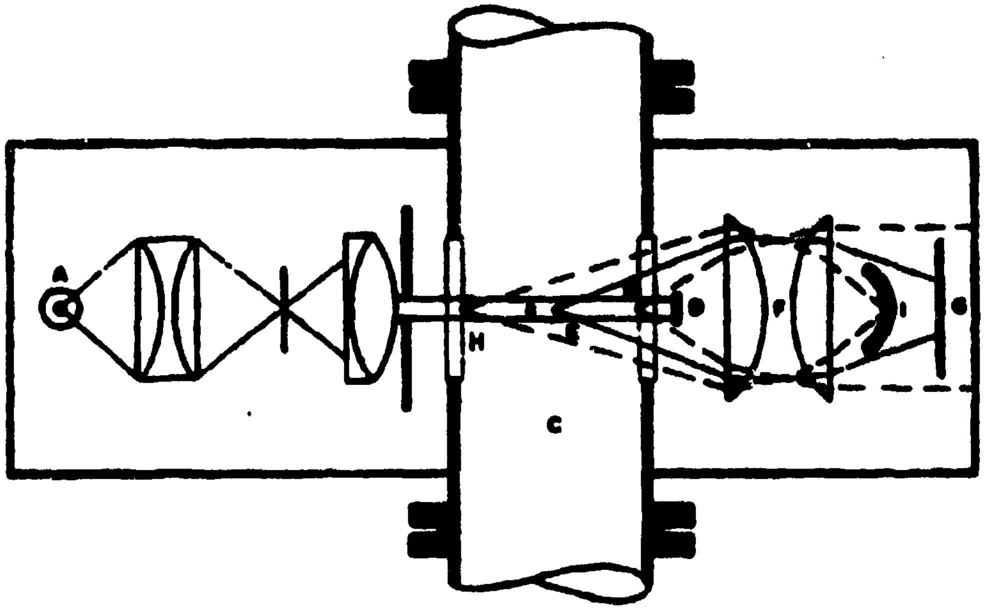


FIGURE 5-12. OPTICAL SCHEMATIC OF IN-LINE FORWARD SCATTERING TURBIDIMETER

Historically, forward scattering units were not widely used due to difficulty in distinguishing among forward-scatter signals produced by the sample, the stray light from the source, and window scattering from the unscattered direct beam. With the solution of these problems, the forward-scatter technique became capable of providing substantially greater sensitivity, and when combined with direct beam measurements, the instrument could be made insensitive to color and color changes in the sample. Furthermore, because an increase in the size of the scattering particle increases the (particle's) scattering efficiency as the square of the radius, as well as increasing the forward component of the total scatter pattern, the forward-scatter signals are more closely related to the mass concentration of the particles than are back and side-scatter signals.

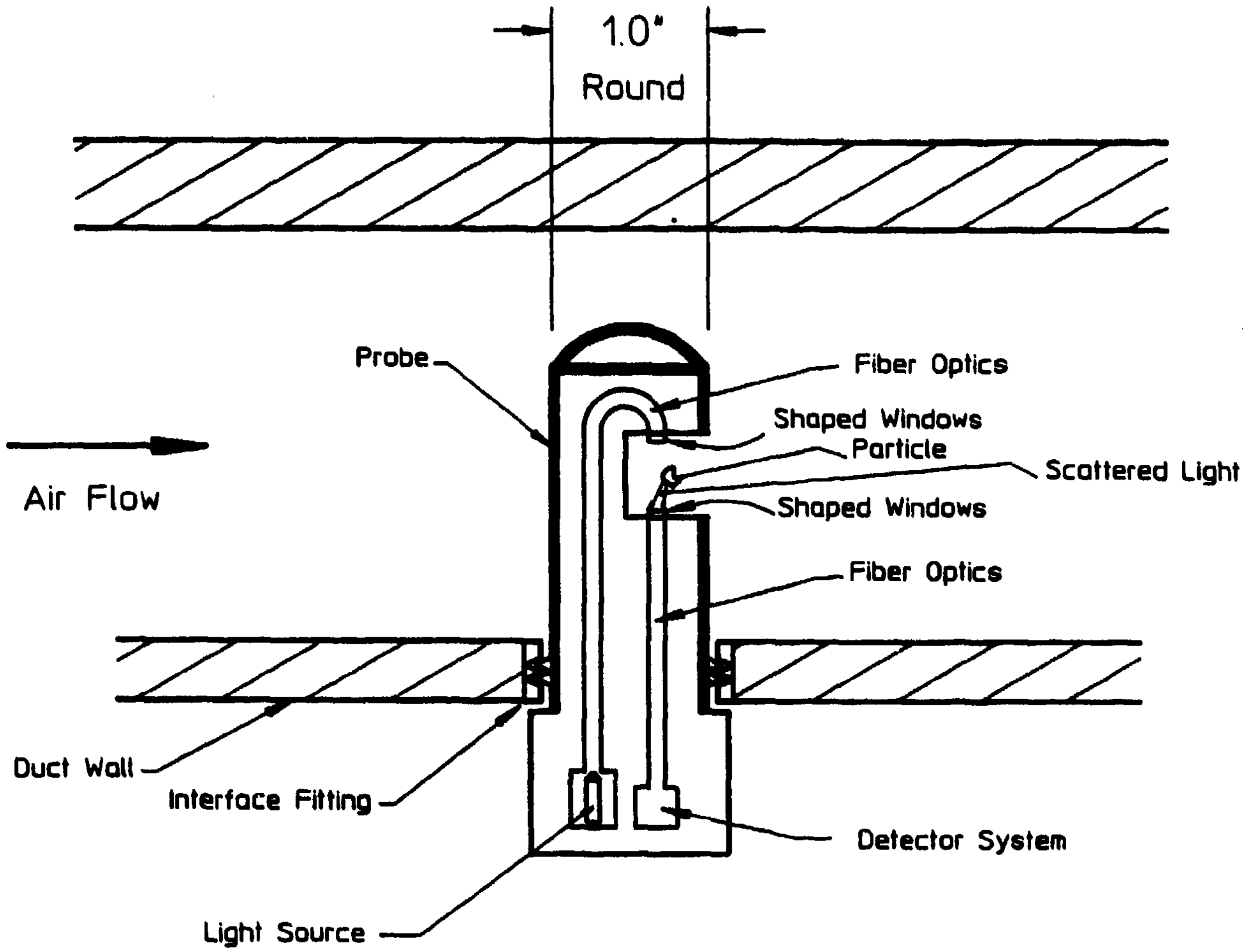
During first round testing, the instrument's response to the larger particles (in our range of interest) was generally good, although there was indication of a need to increase sensitivity to improve particle discrimination and to facilitate a "go"/"no go," step type response at the threshold setting. MONITEK advised that this would require a relatively easy change, and upon review of the test data, decided to provide an upgraded unit for second round testing.

Whereas the initial instrument operated by having the sensor and transmitter on opposite sides of the duct, the instrument designed for second round testing consisted of a single probe that could be inserted into the duct, and which contained the light source and the detection system on the same side. This was accomplished by using a fiber optic link which transmitted light from the source to a window so that the beam was directed back toward the detection system. This probe is shown schematically in Figure 5-13. In addition, the actual probe tested is shown on the test bench in Figure 5-14. This probe is much larger than the probe that would be designed for the on-vehicle applications.

Prior to shipment to SwRI, the unit was calibrated by MONITEK on liquids, as was the previous unit, but not optimized for our application because of a lack of time. As such, there was some concern that the scattered light would be too diminished and this turned out to be the "weak link." After initial second round testing and several attempts at troubleshooting, the unit was returned (twice) to MONITEK for repairs and/or adjustments. Because of time constraints, it was eventually necessary to abandon the MONITEK unit.

Although second round testing of the MONITEK unit could not be completed because of complications and problems within the instrument's design circuitry, results for those tests that were accomplished indicate that a higher intensity light source will be needed to provide an adequate instrument response. This can be accomplished in several ways; for instance, by increasing the lamp voltage or by changing from incandescent to a solid-state light source, such as a laser. In spite of the illumination problems experienced, it should be emphasized that the MONITEK technology is worthy of consideration.

5.3.6. HIAC/ROYCO. The HIAC/ROYCO detector provided for first round testing was an extraction type unit that was designed to use the HIAC/ROYCO Model 4100 particle counter (on-hand at SwRI) for output. As with the other detectors, the sensor was not designed for our specific application, but was being tested to demonstrate the potential of the technology through a series of proof-of-concept experiments. The unit, which contained proprietary optics and electronics, was calibrated over a particle size range of 7 to 200μm, at an air flow rate of 100 milliliters per minute (see Figure 5-15). Although this was a very small flow rate (with respect to our application), it was required by the sensor since the residence time of a particle in the laser diode beam determines the pulse width of the signal and the signal's duration, which were matched to certain electronic time constants in the circuitry. In order to avoid misleading data, the flow rate through the



NOTE:
Probe shown rotated 90° about verticle axis.

FIGURE 5-13. SCHEMATIC OF MODIFIED MONITEK PROBE FOR SECOND ROUND TESTING

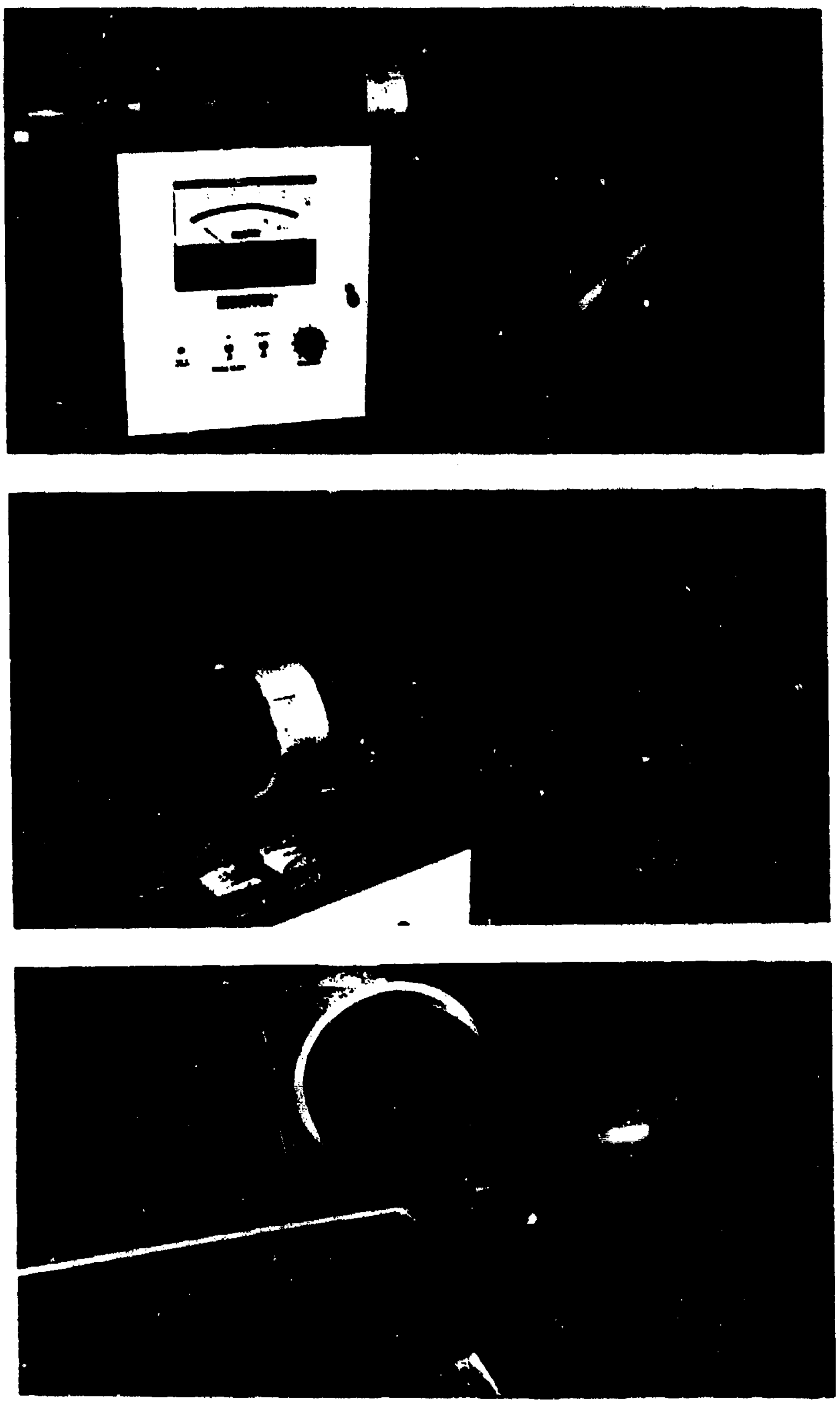


FIGURE 5-14. MONITEK PROBE DURING SECOND ROUND BENCH TESTING

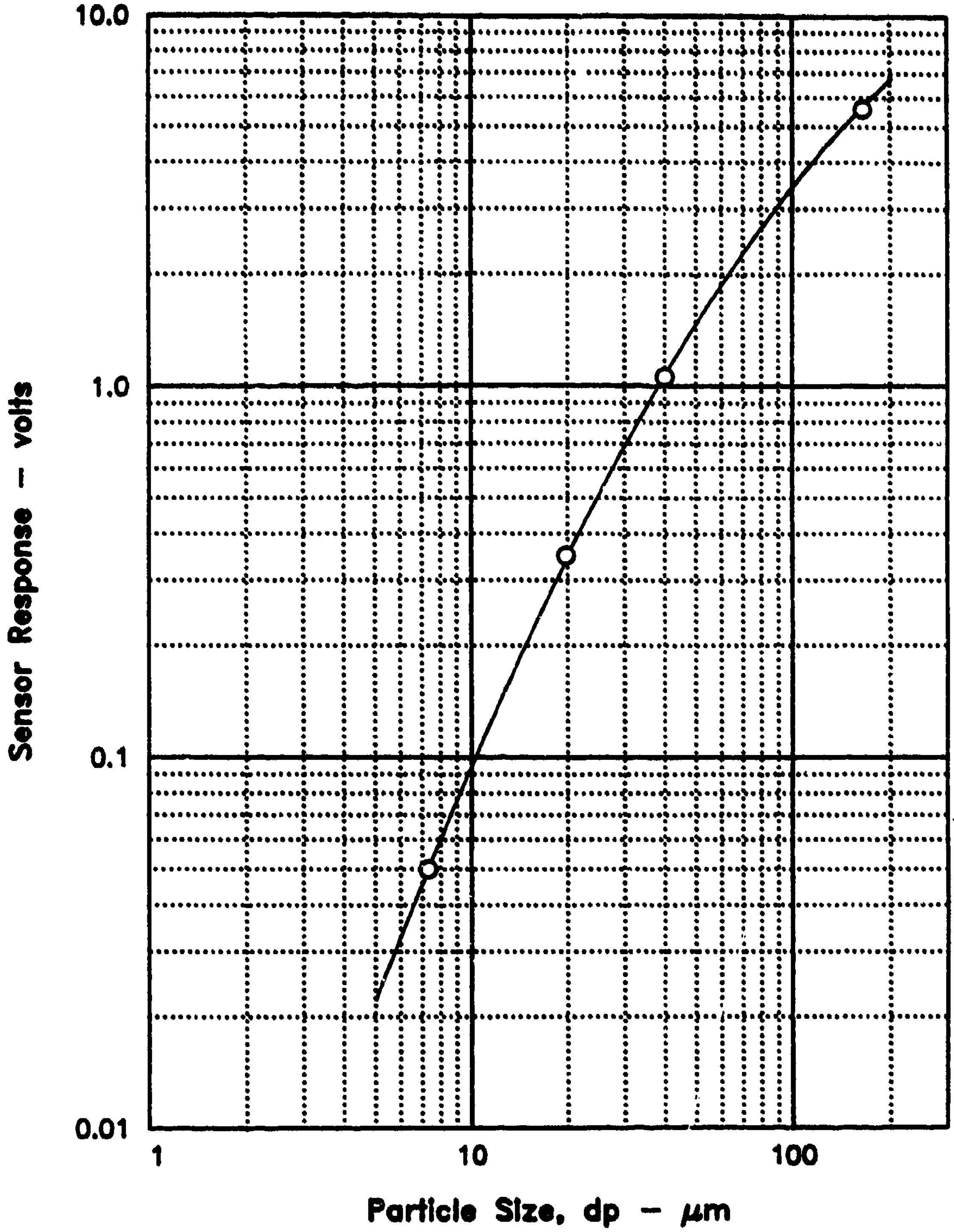


FIGURE 5-15. CALIBRATION CURVE FOR INITIAL HIAC/ROYCO; ROUND ONE TESTING

sensor cell was kept constant, although a fluctuation of ±50 percent of the nominal flow would have been acceptable. This unit, identified as a Model LD400, (S/N PR01) prototype, is shown in Figure 5-16.

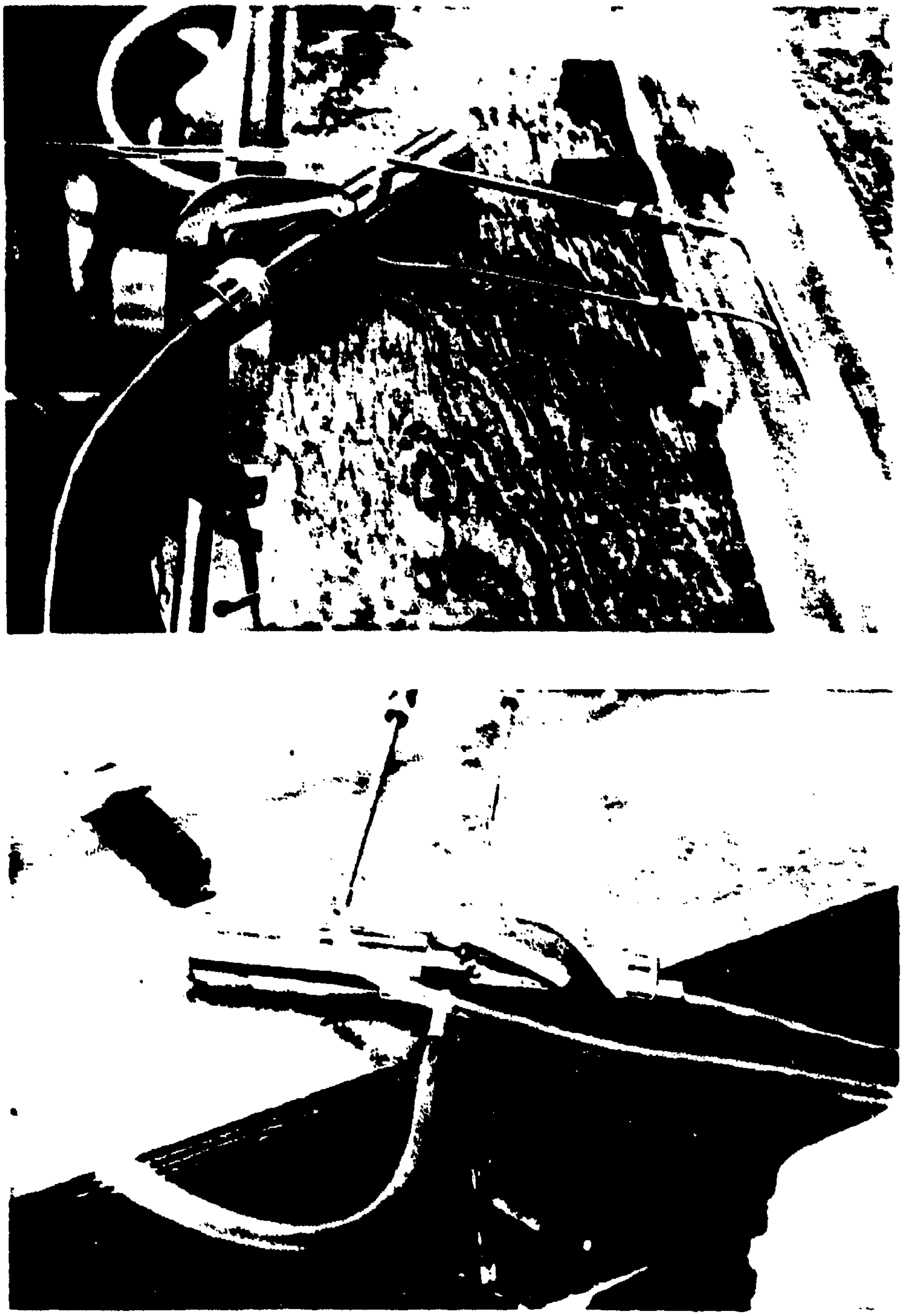


FIGURE 5-16. INITIAL HIAC/ROYCP EXTRACTION TYPE PROBE (MODEL L0400, S/N PR01)

The unit was tested by alternately attaching the prototype sensor port and the HIAC 1200 sensor port to the HIAC 4100 counter during each test run. Once the dust concentration level and particle size distribution of interest was established, as shown by the HIAC output using the mainstream sample probe and 1200 sensor, several switches were made so that back-to-back readings could be accomplished. In this way, it was possible to compare the output from the experimental sensor with the output from the laboratory standard. Results indicated that the technology, with certain modification, appeared feasible.

For the second round prototype, a decision was made to pursue an in-situ detector rather than continue with flow sampling and remote sensing. HIAC/ROYCO had been working on a new, in-line sensor for aerosol applications and this sensor was known to provide better light sensitivity and resolution. Consequently, this sensor formed the basis of the second round prototype, which is illustrated in Figure 5-17. The unit is shown undergoing second round testing in Figure 5-18.

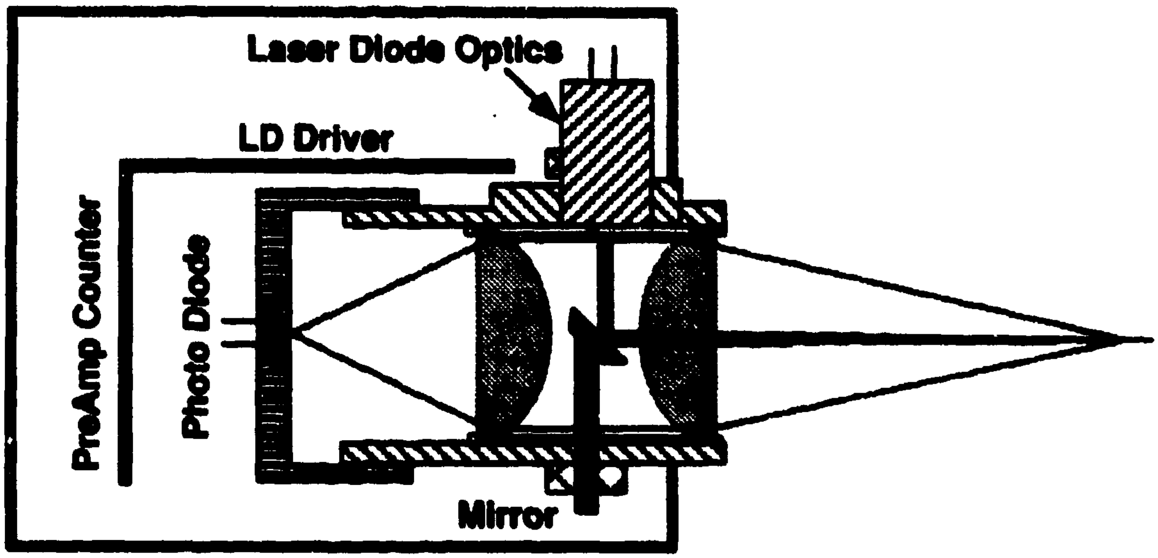


FIGURE 5-17. ILLUSTRATION OF HIAC/ROYCO SECOND ROUND PROTOTYPE

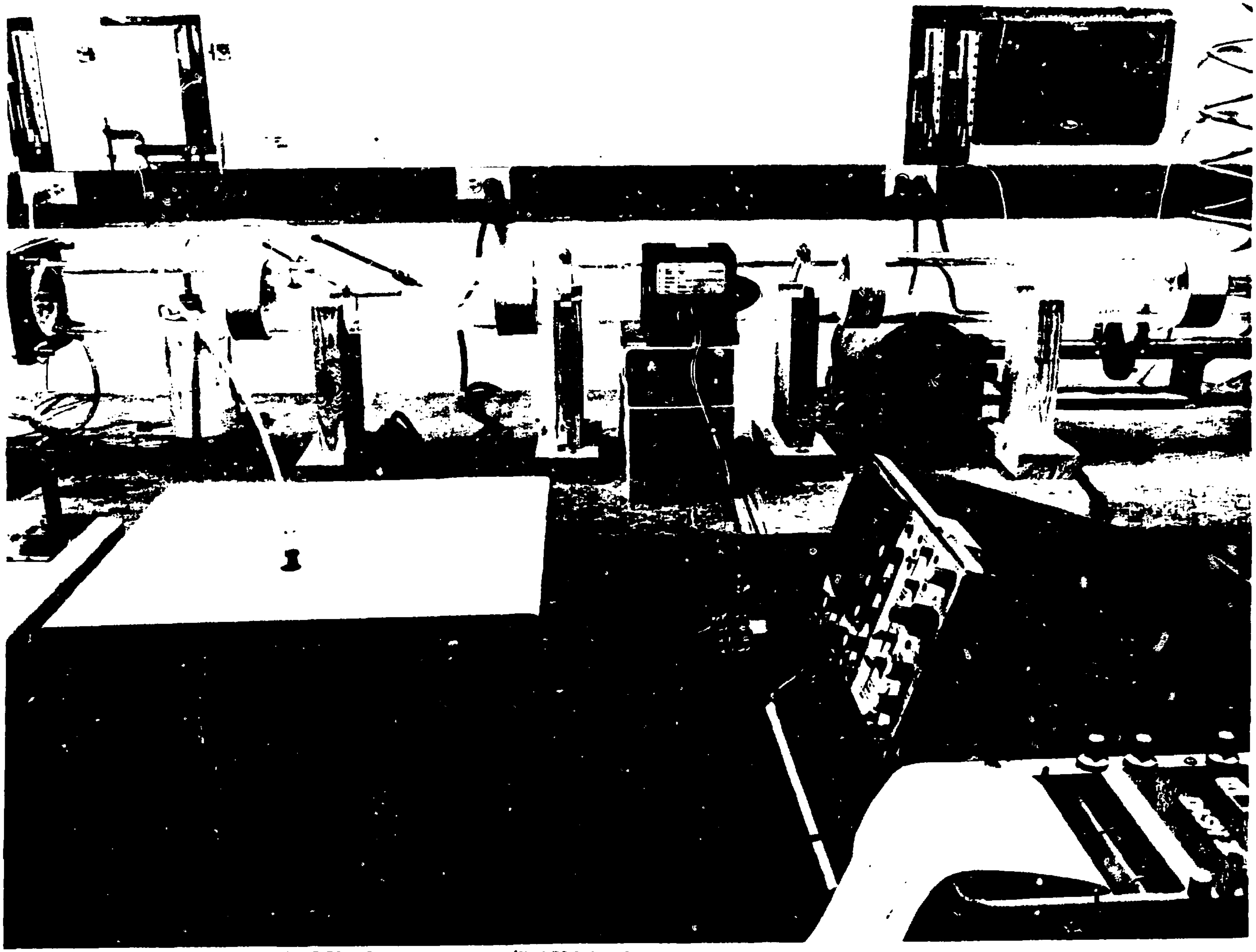


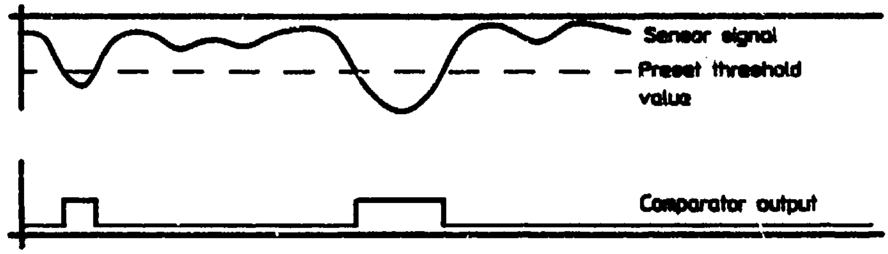
FIGURE 5-18. HIAC/ROYCO PROTOTYPE UNDER SECOND ROUND TESTING

The detector's optical sensor is based on the back scattering concept. A collimated laser diode beam is focused through a lens into the flow stream. Light is scattered by dust particles backward in the direction of the same lens, which, with the help of a second lens, images the scattered light at a point on the photo diode. The laser beam is redirected between the two lenses by a mirror, and since the beam is collimated, its intensity will be at a maximum in the focal point of the front lens. The area of high light intensity around this focal point defines the measurement volume of the detector, and since only back-scattered light will be collected by the lens, detection is limited to those particles passing through this region that back-scatter light of high enough intensity to be recognized by the photodetector. The self-aligning concept of the optics makes this sensor very insensitive to vibrations, component variations, and thermal expansions. Because the instrument optically defines the sensing volume within the duct, it can be considered <u>in-situ</u>. While this alleviates many of the problems associated with extractive sampling and particle transport, the instrument's sensing zone is still sensitive to spacial location within the duct as far as sensing "representative" particles is concerned.

The optical signal at the detector depends mainly on particle size and the intensity distribution of the laser beam. In practice, the optics form a beam of varying brightness across the active measurement volume. This beam is a very bright line along the beam axis in the center, while gradually decaying in intensity at the beam edges. Since a large particle passing through the edge of the beam generates as much signal as a smaller particle passing through the beam center, and since all signal pulse amplitudes are compared to a threshold value, with pulses exceeding the threshold being processed further, the sensor is effectively counting large particles more efficiently than small particles. (A small particle must pass through the center of the beam to generate enough signal to be counted.) This is exactly the behavior desired in evaluating the different contamination levels caused by acceptable and failed filter elements.

The unit was designed to operate over a wide range of air velocities and to provide in-duct concentration data that are independent of flow. This was accomplished by making the sensor's signal <u>amplitude</u> (<u>pulse height</u>) independent of flow over a wide range of in-duct velocities. However, at the higher flows, <u>pulse width</u> was shortened because the residence time of the particles in the light beam was smaller. Thus, for a fixed level of air contamination, a high flow would cause a relatively large number of "skinny" pulses to pass the threshold comparator, whereas a low flow would cause fewer wider pulses to pass. The fraction of time that the comparator remained high; that is, the net pulse width counted over a given period of time was the same. This counting arrangement is illustrated in Parts A and B of Figure 5-19, where the sensor signal, comparator output (pulses) and

a) Low Flow



b) High Flow

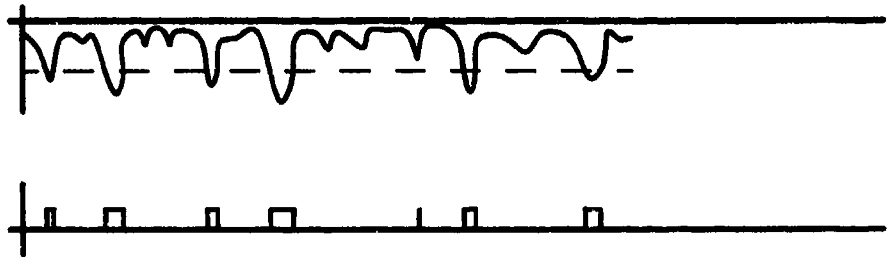


FIGURE 5-19. ILLUSTRATION OF HIAC/ROYCO COUNTING ARRANGEMENT; SENSOR SIGNAL AND COMPARATOR OUTPUT FOR LOW AND HIGH AIFLOWS

comparator limit are shown for similar concentrations at low and high flow rates. Simply counting the number of pulses or the pulse rate, however, would report higher contamination at higher velocities, which is not appropriate. On the other hand, the duty cycle of the pulse train (that is, the fraction of the time the comparator is high) corresponds directly to the contamination level, independent of the flow rate.

Three interacting parameters are therefore required to determine the sensor's response with respect to the "go"/"no-go" triggering conditions: the signal threshold level, the sensor's duty cycle limit value, and the integration time for duty-cycle determination. For example, the signal threshold setting instructs the comparator as to what pulses to count (process further) based on particle size (pulse height). Also, a signal threshold set for high sensitivity; for instance, responding to 5μm particles, might call for a duty cycle limit of 50 percent, while a low sensitivity setting, say for 10μm particles, might require a duty cycle limit of only 0.1 percent. (Recall that duty cycle is defined as the ratio of the pulse width for particles greater than the threshold value to the pulse width for particles less than or equal to the threshold value, which in this case is 7μm.)

For evaluation purposes, the signal processing circuit must, therefore, accommodate a wide range of duty cycle adjustments. Also, the integration time must be adapted to the application. A long integration time gives a slow response but avoids false alarms due to small particle bursts. The integration time requires adjustment from a fraction of a second up to several seconds.

The diagram presented in Figure 5-20 illustrates the approach to signal processing, and the block diagram in Figure 5-21 shows the signal processing electronics. The pre-amplified signals consist of negative-going pulses of Gaussian shape. The pulse widths will vary from about 20μs at maximum flow velocity to about 1 millisecond at lower flows. As shown in Figure 5-22a and b, pulses exceeding a certain threshold voltage pass the comparator as digital pulses, which are then timed by gating a high-frequency clock (C). The pulses are accumulated in a counter for a pre-set integration time (D). If the accumulated count exceeds a limit value, an output relay is activated (E). A retriggerable one-shot keeps the relay on long enough to ride through the next integration period (F), while the counter is reset at the end of each integration period. The integration time is set through selectable divider chains so periods of approximately 128μm to 256μm. . . 16.192s are available. The duty cycle counter is set with a similar chain for a prescaler followed by a comparator which allows precise setting of the limit. It is important to note that of the dust detectors evaluated, the HIAC/ROYCO unit is the only detector that addressed the concentration issue directly.

Several modifications were proposed for the HIAC/ROYCO unit to develop the sensor beyond the prototype stage. Size would be reduced to allow the unit to conveniently fit near the engine since it is likely the sensor would mount at the intake manifold. Placing the sensor at this end of the flow path would allow it to monitor the entire air induction system and therefore it could detect dust leakage from other components, such as loose hoses, flanges, and such, as well as from a faulty air cleaner system. Figure 5-22a shows a redesign which places the full optical and electronic system in a single compact module. This module could screw directly into the manifold inlet port through a 1-inch pipe thread insert. The production sensor must also survive the extremes of temperature and vibration consistent with military vehicle operation.

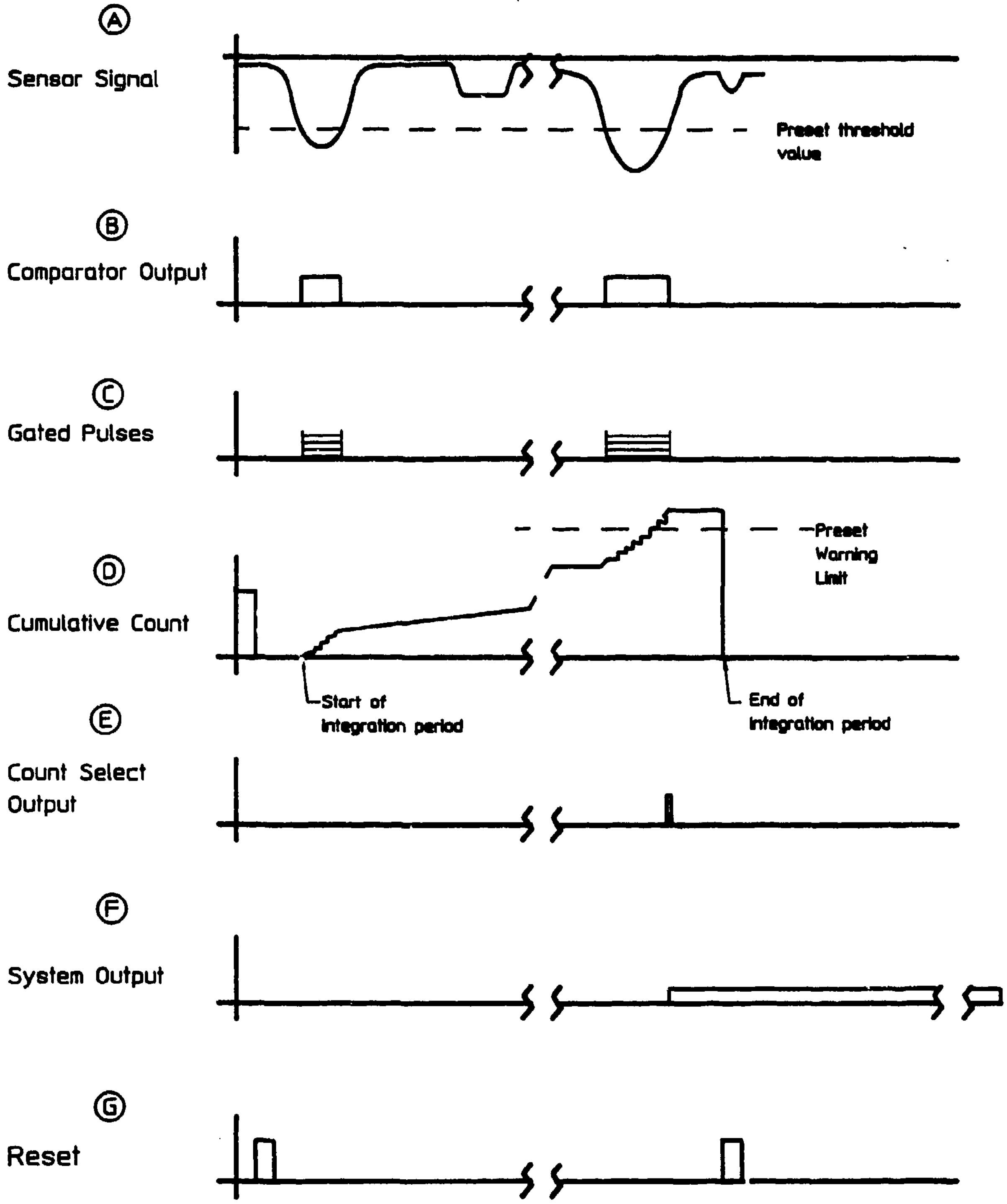


FIGURE 5-20. HIAC/ROYCO APPROACH TO SIGNAL PROCESSING; SECOND ROUND PROTOTYPE

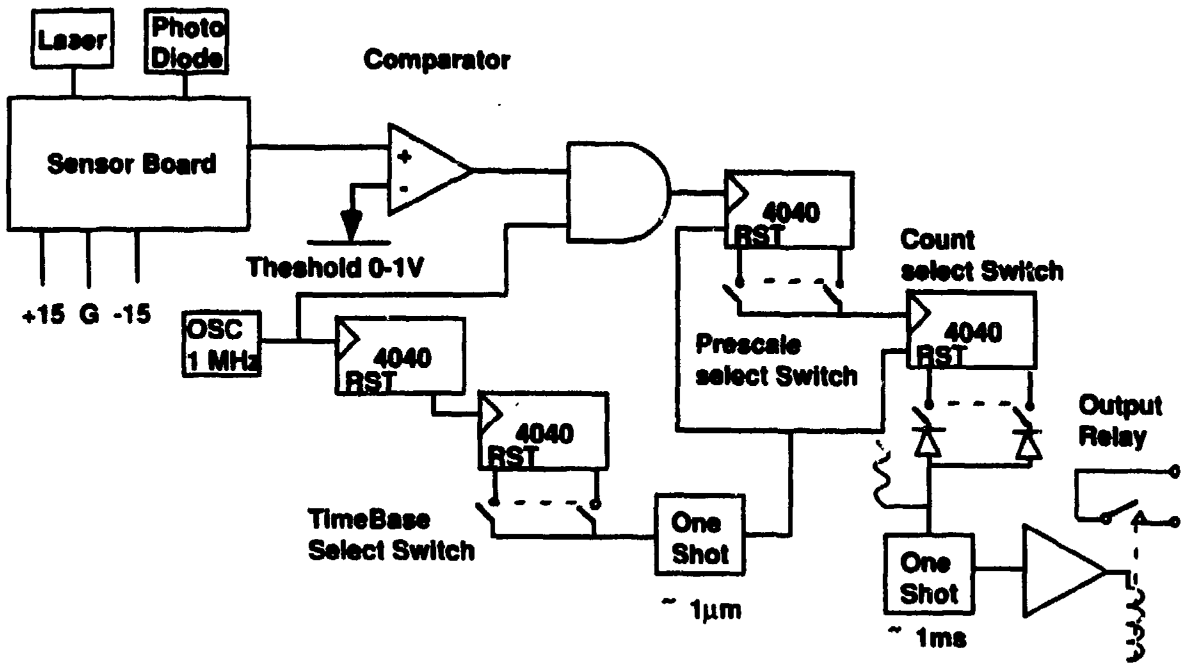


FIGURE 5-21. SYSTEM BLOCK DIAGRAM OF HIAC/ROYCO SIGNAL PROCESSING ELECTRONICS

Figure 5-22b shows a preliminary design which would include:

1. An internal die cast frame holding the optical and electronic subassemblies in stable alignment. A compliant mount between the internal frame and the housing would accommodate differential thermal expansion.

2. The sensor is gasket-sealed against liquid, air, and dust entry.

3. The internal structure is temperature stabilized by a Peltier heat pump. This enhances reliability at high external temperatures.

4. The electronic functions are implemented with low parts count, using one or two ASIC chips on hybrid ceramic substrates.

5. A rugged cast housing with integral wrench flats protects the unit from handling abuse.

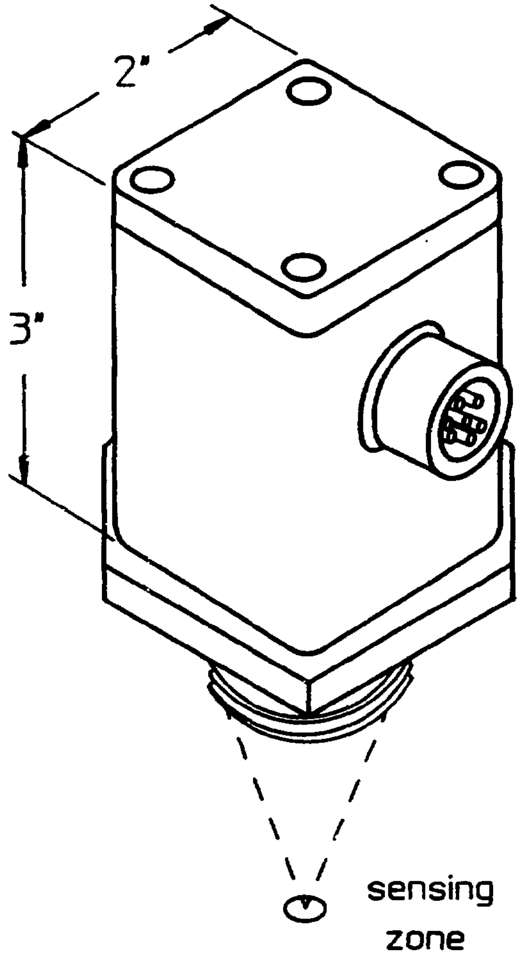


FIGURE 5-22A. PROPOSED HIAC/ROYCO UPGRADE: EXTERNAL VIEW

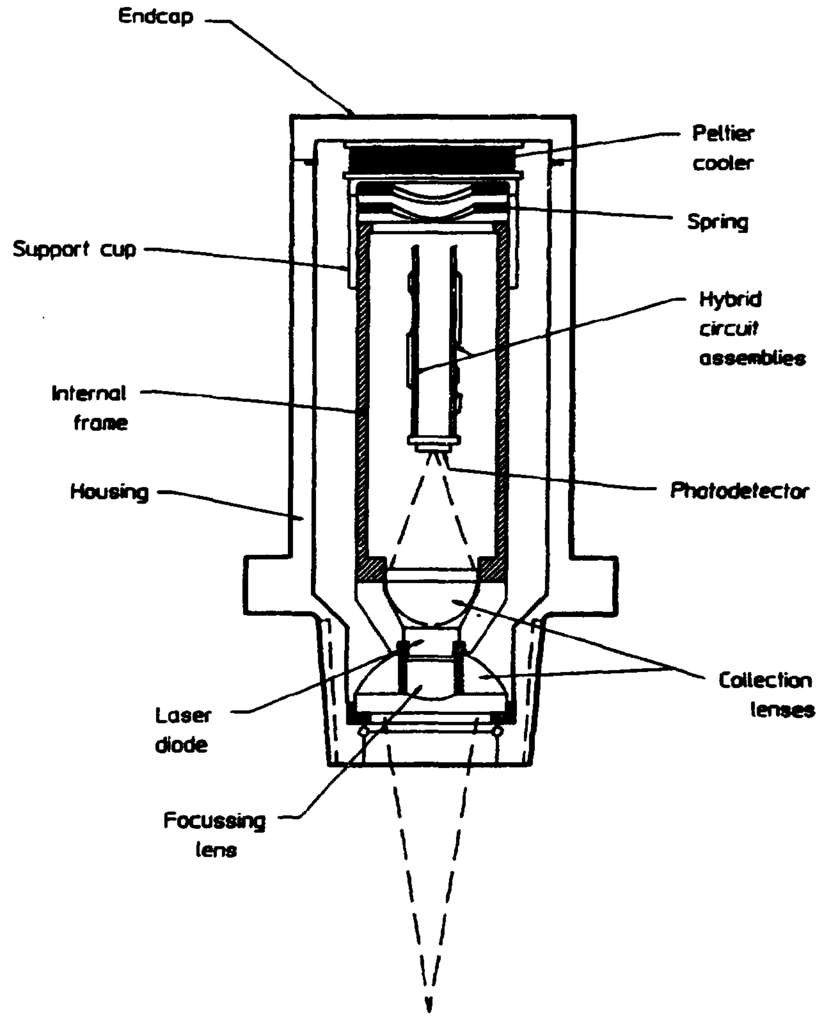


FIGURE 5-22B. PROPOSED HIAC/ROYCO UPGRADE: MAJOR INTERNAL COMPONENTS

The unit would also be designed to protect against internal contamination. The current prototype design allowed some dust to collect on the sensor lens. This dust could backscatter light into the detector, possibly degrading performance. The coaxial illuminator design, shown in Figure 5-22b, prevents this effect and substantially improves the sensor's tolerance to dust deposits.

The detector must also respond positively to a fault condition without toggling on and off. The prototype's poor performance in this area can be improved by extending the integration time. In addition, hysteresis could be employed using a lower threshold to turn off the warning than to turn it on. These changes would provide an unambiguous signal to the operator.

It is anticipated that the next development phase would include building a second-generation prototype with coaxial optics, refining the signal-processing parameters, and performing laboratory dust tests. Following that, a number of ruggedized samples could be build and subjected to environmental tests. After preliminary qualification, the samples would be installed on operational vehicles for field trials. Refinements based on results of these trials could be incorporated into the final design.

5.3.7. TSI. The initial TSI prototype submitted for first round testing and evaluation consisted of an insertion-type probe and an electronics box, as shown in Figure 5-23. The sensor installs directly into the engine intake by means of a threaded fitting attached to the intake wall. Once inserted, the sensor would be aligned by means of an arrow inscribed on the case showing proper flow direction. Because of the probe's design (reference Figure 5-23), proper alignment is essential for proper operation, and in this regard, the alignment method was considered too subjective, with no physical means for assuring that the required alignment would be "locked in" and maintained.

Details of the sensing assembly and the optical lay-out within the sensing assembly are given in Figure 5-24. Particle contaminants pass through the sensing zone with a portion of the air flow in the duct. As with other probes, location of the sampling area; that is, the location of sensing volume within the duct, and the particle and velocity fields in the vicinity of the probe will be important for accurate particle sensing.

As shown in the optical lay-out, light from a 5 miliwatt laser diode is focused to form a spot at the middle of the aerosol sampling area. A light stop traps the main beam in front of receiving lenses to prevent the main beam from entering the photodetector. As particles pass through the focused part of the laser beam, they scatter light which is picked

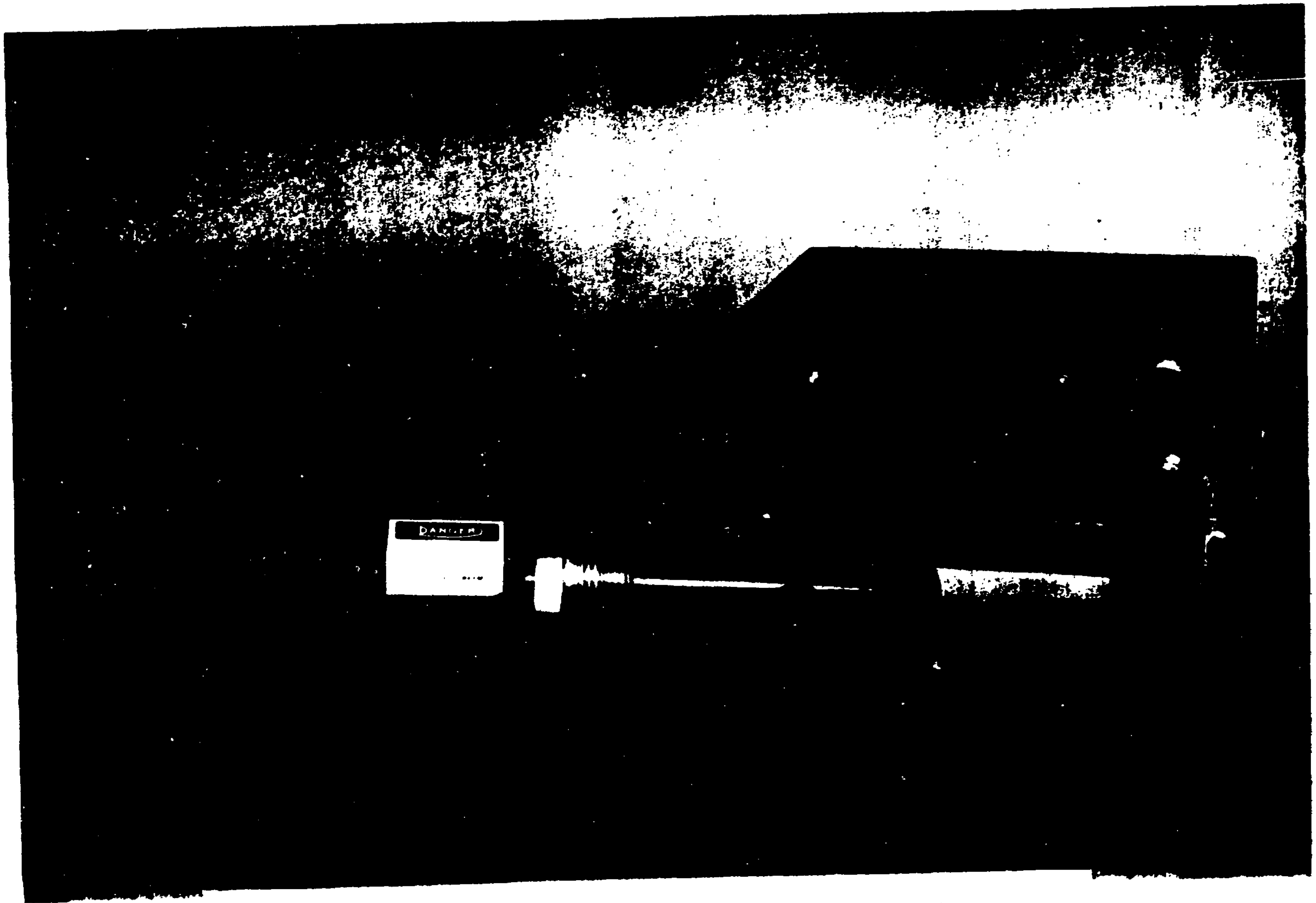


FIGURE 5-23. INITIAL TSI PROTOTYPE DETECTOR; INSERTION PROBE AND ELECTRONICS CONTROL BOX

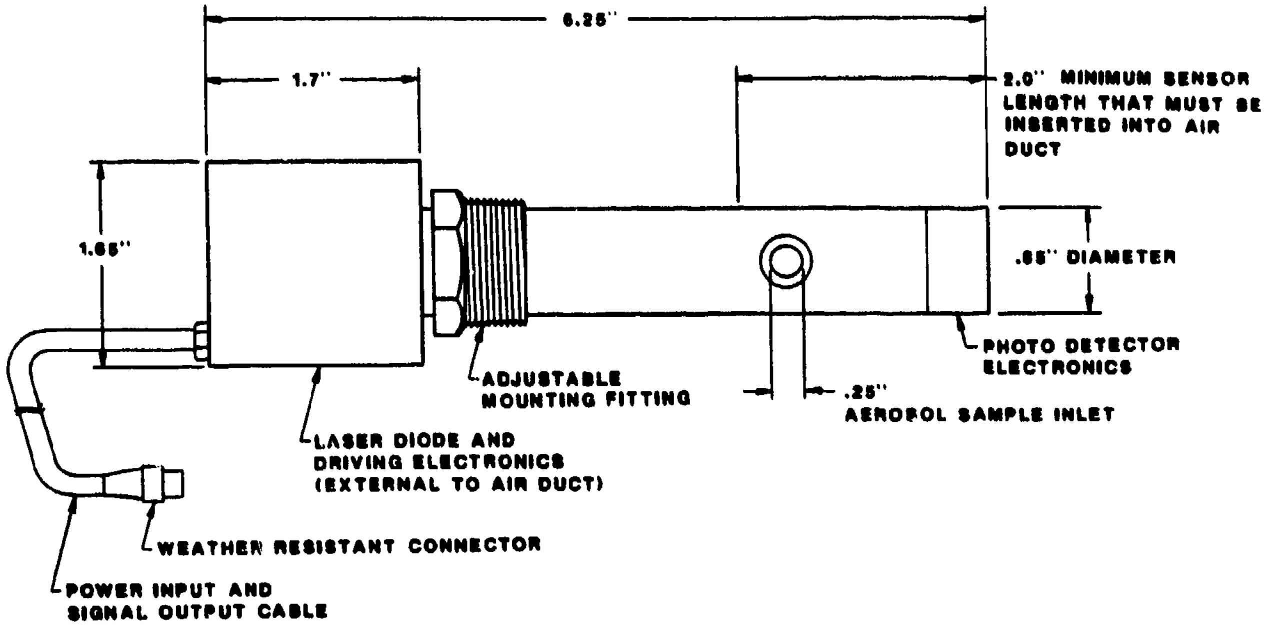


FIGURE 5-24A. DETAILS OF TSI INSERTION PROBE: SENSING ASSEMBLY

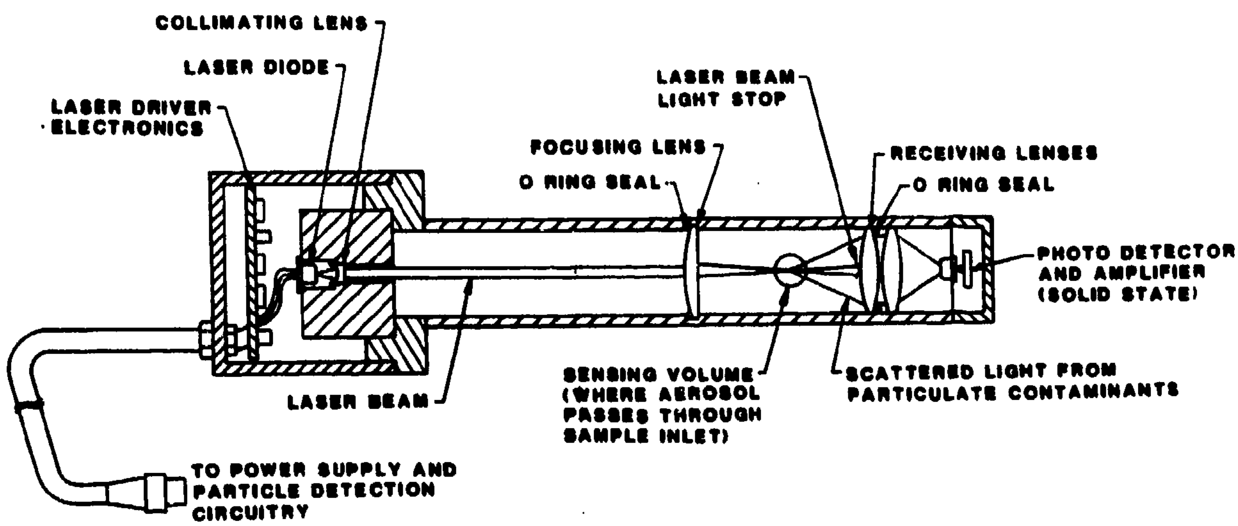


FIGURE 5-24B. DETAILS OF TSI INSERTION PROBE: OPTICAL LAYOUT

up by the photodetector and converted to electrical pulses, which are processed by an electronic circuit located inside a separate unit. Electronic monitoring of the photodetector output is accomplished by two circuits. The primary circuit is sensitive to the AC component of the photodetector signal, which results when particles pass through the measuring volume. This circuit is intended to alert the user should the concentration of particles become too high. Output from the primary detector can either be a pulse for every particle greater than a selective size, or a voltage that is dependent on the number of particles and particle size. When used in the voltage mode, the sensor output is much higher for larger particles than for smaller particles.

The second monitoring circuit is sensitive to the DC component of the photodetector signal. This component is caused by stray light from the lenses and other internal sensor parts, and can be used as an indicator of sensor condition. For example, dirty lenses will scatter more stray light, thus the DC signal can be used to indicate the need for servicing, although TSI claims the sensor can tolerate a relatively high amount of dirt and contamination without need of servicing. A defective laser diode would be detected as low or zero stray light.

First round bench test data for the TSI instrument were difficult to interpret because the instrument was provided without any type of calibration relating output to particle size, and because the exact size of the sensing zone was not known. As a result, there was no direct way to accurately correlate the unit's count data (for various voltage cut-off settings) with the HIAC data, which were directly related to in-stream concentration levels. In the absence of calibration data, if beam diameter (at the focal point) had been known, reasonable correlations could have been attempted, as illustrated in Figure 5-25. As shown, beam diameter could have been used to calculate the beam's cross-sectional area, and together with flowrate information, to infer the volume sampled for a given time period. In this manner, the TSI count data could have been converted to concentration, and these results examined against the HIAC data.

TSI speculated that the (focal point) beam diameter might be 20 or so μm, with broadening away from the focal point; however, using this value produced inappropriate results.

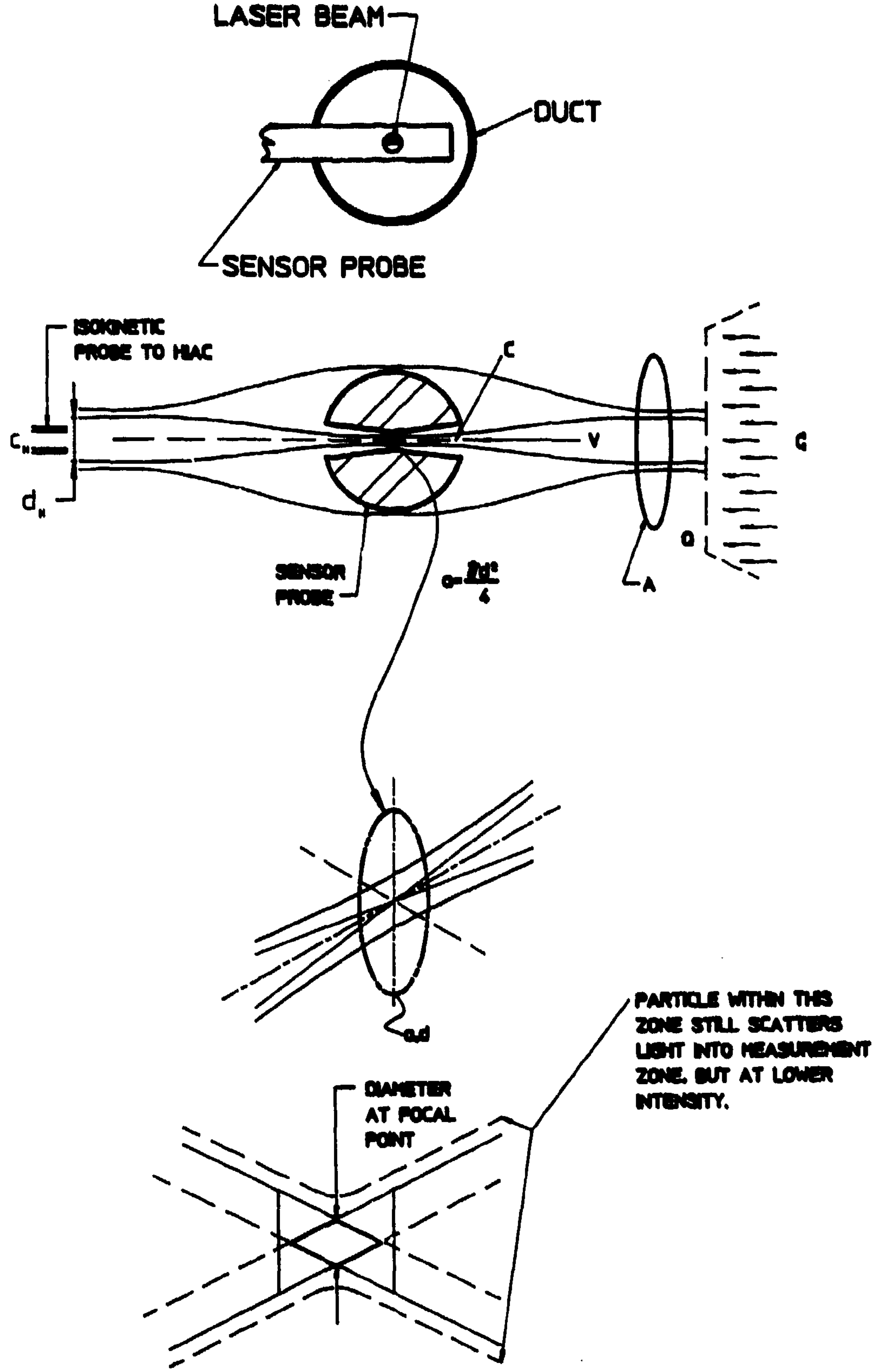


FIGURE 5-25. ILLUSTRATION OF SAMPLING MECHANICS FOR TSI PROBE

To a first approximation, the flow through the probe area is assumed to be isokinetic with respect to the mainline flow (actually, some velocity speeding is expected due to probe geometry). Thus

$$q = Va = \frac{Qa}{A} = Q\left(\frac{d}{D}\right)^2 \tag{2}$$

and the number of particles available to the sensor becomes

$$N = cqt = CQ\left(\frac{d}{D}\right)^2 t \tag{3}$$

since c = C. Therefore,

$$C = N\left(\frac{D}{d}\right)^2 \left(\frac{1}{Qt}\right) k^2 \quad [\#/ft^3] \tag{4}$$

$$= N\left(\frac{D}{d_s}\right)^2 \left(\frac{1}{Qt}\right) \tag{5}$$

where $k = d/d_s$, where d_s is the diameter of the laser spot, since only particles passing through the spot are counted. Depending on the voltage setting, d_s may average to include the fringe area adjacent to the beam, as well as a portion of the widened area away from the focal point. Equations (4) and (5) give sensor and mainstream concentration in terms of the measured and set or known parameters: N is sensor count; Q, t, D and d are set or fixed, and d_s is slightly variable, depending on the set point voltage. Comparison of C from Equation 5 with "C" as determined from the HIAC, as a function of particle size, gives an (approximate) indication of sensor performance.

Since d_s was not known, and since no pretest calibration had been conducted to delineate the voltage-size relationship, another approach was taken in an effort to reconcile the TSI raw count data. This approach, which examined the TSI response, for a given voltage setting, based on particle counts for given dust distributions as measured by the HIAC, is illustrated in Figure 5-26. Here, curves A-D show the HIAC responses in terms of cumulative numerical concentration for particles ≥dp, at a given sensor voltage setting. The TSI sensor count, which is also a cumulative value, is superimposed on the HIAC data for corresponding test runs. Collectively, these data, if the sensor's response is consistent,

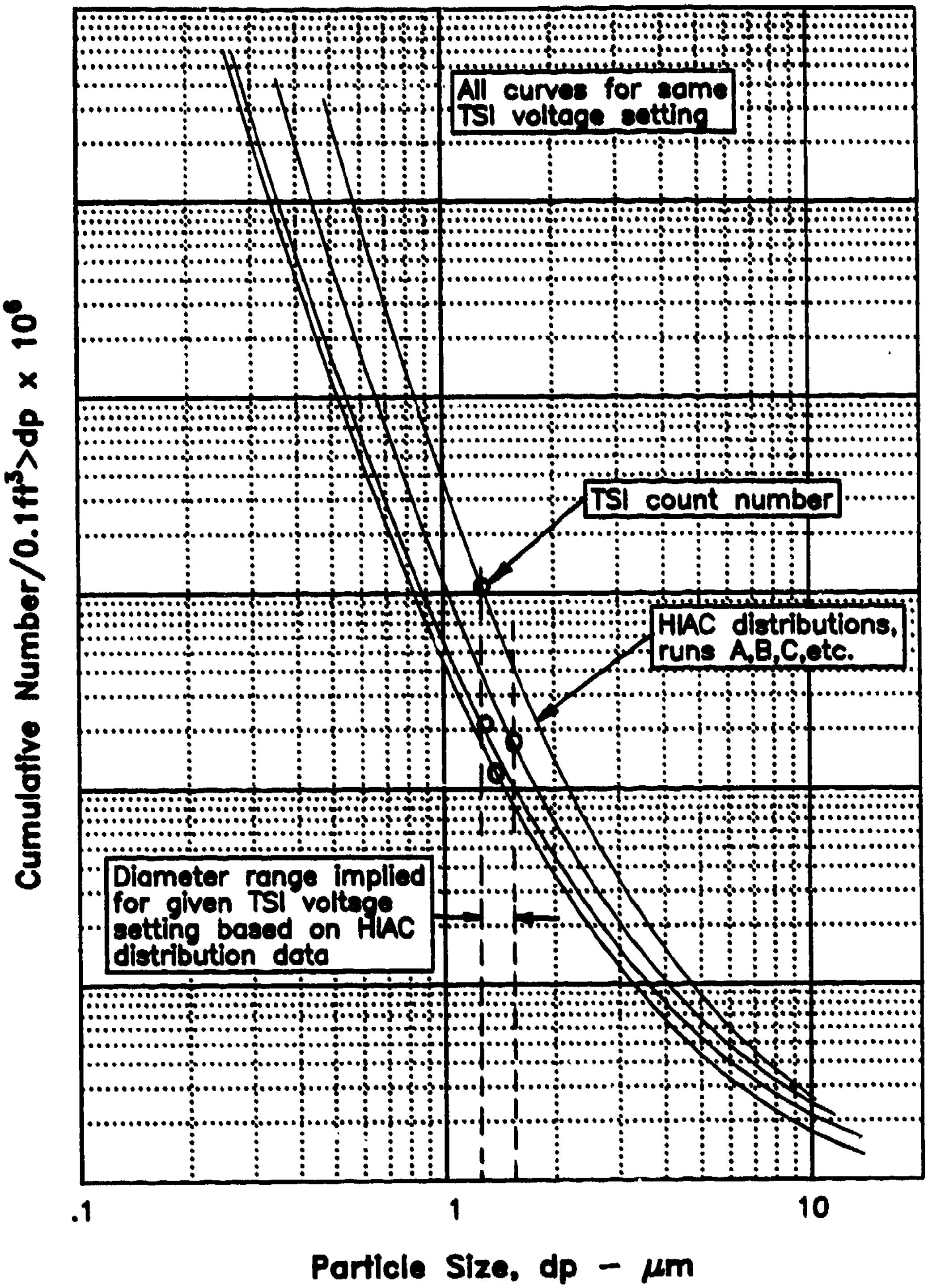


FIGURE 5-26. ILLUSTRATION OF SCHEME FOR ANALYZING TSI DATA, FIRST ROUND, BENCH TEST

were not sufficiently consistent to assure the rigorous test-to-test correlations needed to define the sensor's threshold setting. Part of the problem was the variability of d_g with voltage setting. In addition, the TSI sensor did not address concentration as a function of variable airflow.

At the end of round one, an upgraded unit was developed, based on the triggering criteria and specifications given in our program. This unit was returned for second round testing, but was withheld at TACOM's request, and eventually dropped from the program because it was being pursued under another effort.

5.4. Trade-Off Study

In order to investigate and somewhat quantify the performance of the early instruments, a trade-off study was conducted to rank relative performance and to measure performance against certain minimum requirements. Since most of the instruments were laboratory prototypes, which were primarily intended to demonstrate proof-of-concept with respect to particle sensing capability and to infer overall system function, they were not intended, or expected, to meet military operational requirements, although their potential for doing so was an important consideration in assessing expected overall performance capability.

Early in the project, a preliminary set of revised trade-off parameters were submitted to TACOM for considera Table 6. After some refinement and consolidation, a list of parameters, with importance or weighting factors, was developed. These parameters, given in Table 7, along with their weighting factors, are defined in Table 8. Of the three major parameters, particle sensing was investigated experimentally, whereas vehicle operation and cost were mostly investigated analytically. This approach was consistent with the fact that the trade-off study was intended to evaluate potential performance, as well as measured performance, since the instruments were essentially prototypes (intended to demonstrate a concept or particular technology) rather than well-developed production or pre-production units.

The methodology governing the trade-off study is illustrated in Table 9. Here, each major parameter and subgroup parameter was assigned an importance (weighting) factor (X, Y, x_a, y_a) and rating value (r_{b1}, r_{b2}, etc.) which, in effect, assigned a numerical score or rating from zero to ten (lowest to highest worth) as a measure of the instrument's actual performance or, where appropriate, an estimate of its potential performance. The total weighted score for each unit, which was the sum of the products of the weighting factors

TABLE 6. PRELIMINARY TRADE-OFF PARAMETERS SUBMITTED TO TACOM FOR CONSIDERATION

Major Trade-Off Parameters

Particle Sensing Requirements

- Potential for particle size and concentration discrimination ability relative to set-points in range of interest -- dynamic range
- Output as a function of dust load at varying airflow rates
- Principle of operation and proof off concept -- method of detection and operation (sample requirements, in situ, see-through, etc.)
- Response time
- Sensitivity
- Repeatability
- Stability (detection ability) as a function of time, dust exposure, etc. (drift and contamination sensitivity; likelihood of dust deposition on sensor and likely impact on performance)
- Alignment sensitivity and difficulty

Operational and Functional Requirements

- Potential for adaptability; likelihood for successful on-vehicle integration (shock, vibration, temperature, size, electronic interface, etc.)
- Life expectancy
- Maintenance requirements (routine, major, calibration, self-test)
- Susceptibility to electromagnetic interference

Cost Factors

- Initial cost
- Life cycle cost

TABLE 7. REVISED TRADE-OFF PARAMETER MATRIX, WITH IMPORTANCE FACTORS

Major Parameter	Importance (weighting) Factor	Unit 1	. . .Unit N	Comment
Particle Sensing Requirements (dynamic response and function)	**0.40**			
• Sensitivity to particle size	.25			
• Sensitivity to particle concentration	.25			
• Response time	.20			
• Stability	.15			
• Sensitivity to alignment or position	.15			
• Other*	.00			
Operational Requirements	**0.40**			
• Vehicle compatibility	0.40			
• Reliability	.30			
• Environmental resistance	.20			
• Maintainability	.10			
Cost Factors	**0.20**			
• Life cycle cost	.8			
• Initial cost	.2			

* If other subgroup parameters are added, all weighting factors must be adjusted so their sum is equal to 1.0.

TABLE 8. DEFINITION OF SUBGROUP TRADE-OFF PARAMETERS

Particle Sensing Requirement Parameters (dynamic response and function)

- **Sensitivity to particle size** -- Size sensitivity refers to the instrument's response to particle size distributions in terms of how accurate the instrument is in detecting particles* and how consistent the measurements are from time-to-time. Particle sizes on the order of 7μm are of primary interest. The technology must have potential to respond to defined threshold values so it will only count particles larger than a specified size.

- **Sensitivity to concentration** -- Concentration sensitivity refers to the instrument's response to particle size distributions at various concentration levels.* Concentrations on the order of 0.25 x 10^6 particles per cubic foot of air for 7μm particles are of primary interest. As with particle size, the technology must be capable of responding to defined threshold values for concentration so that it will only trigger when a set threshold concentration is met or exceeded for particles equal to or greater than a pre-set size.

- **Response time** -- This is a measure of the instrument's ability to respond to changes in the particle size distribution, and to trigger an alarm when a given size-concentration threshold level is exceeded. The response time requirement is five seconds, with "false" signal discrimination.

- **Stability** -- Stability refers to the absence of errors or deviations from standard conditions over time that could be caused by inherent fluctuation within the instrument such as component deterioration with age, dirty optics, electronic drift, etc.

- **Sensitivity to alignment or position** -- This parameter is a function of the method of detection or operating basis of the instrument and the manner in which the instrument interacts with the dust environment. Alignment or position can affect instrument response sensitivity and certain instrument alignment or position requirements can affect the instrument's potential for successful integration into the vehicle. In this subgroup, the impact on instrument response due to alignment or position is what is of concern.

Operational Requirement Parameters

- **Vehicle compatibility** -- Scoring values here are based on the likelihood that the instrument components can be successfully integrated into a military vehicle. Considerations include size, method of interfacing with ducting, position/alignment sensitivity, electrical interfacing, etc.

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*AC Fine and AC Coarse test dusts, with their distributions altered by a precleaner and "filter" section.

TABLE 8. DEFINITION OF SUBGROUP TRADE-OFF PARAMETERS (Continued)

- **Reliability** -- Reliability refers to the expected longevity of the design and components, once hardened for military service. In some cases, reliability must consider the expected life of certain state-of-the-art components.

- **Environmental resistance** -- This parameter includes several environmental requirements that must be met to assure compatibility with potential military operating conditions. These include shock, vibration, temperature, EMI, etc.

- **Maintainability** -- Maintainability concerns the instrument's need for calibration, routine and major maintenance, and testing. Self-calibration and self-test features will also be considered. The influence of maintenance on cost will be considered during the life-cycle cost analysis.

Cost Factors

- **Initial cost** -- This factor refers to initial acquisition and installation costs, including unit price based on three or four different ordering quantities.

- **Life-Cycle cost** -- This factor includes the elements for initial cost plus factors representing scheduled and unscheduled maintenance, spare parts, and inventory management.

The relationship between initial cost and life-cycle cost could be an important parameter in determining how dust detectors should be integrated into service and managed. For example, some components may be better classified as "throw away" items rather than repairable items.

TABLE 9. EXAMPLE OF TRADE-OFF STUDY METHODOLOGY

Major Parameter	Importance (weighting) Factor	Unit 1	Unit 2
A	X		
Subgroup parameters:			
a	x_a	$r_{a1}, (r_{a1} \cdot x_a)$	$r_{a2}, (r_{a2} \cdot x_a)$
b	x_b	$r_{b1}, (r_{b1} \cdot x_b)$	$r_{b2}, (r_{b2} \cdot x_b)$
c	x_c	$r_{c1}, (r_{c1} \cdot x_c)$	$r_{c2}, (r_{c2} \cdot x_c)$
.	.	.	.
.	.	.	.
.	.	.	.
	rating score	____, ( )	
	product of rating score and weighting factor		
Total weighted scores for subgroup:		$\Sigma(r_1 \cdot x)$	$\Sigma(r_2 \cdot x)$
Total weighted scores for major parameter:		$X \cdot \Sigma(r_1 \cdot x)$	$X \cdot \Sigma(r_2 \cdot x)$
B	Y		
a	y_a	$r_{a1}, (r_{a1} \cdot y_a)$	$r_{a2}, (r_{a2} \cdot y_a)$
b	y_b	$r_{b1}, (r_{b1} \cdot y_b)$	$r_{b2}, (r_{b2} \cdot y_b)$
.	.	.	.
.	.	.	.
.	.	.	.
Total weighted scores:		$[X \cdot \Sigma(r_1 \cdot x) + Y \cdot \Sigma(_1 \cdot y) + \ldots]_1$	$[\ ]_2$

where: X, Y, ... and x_a, x_b, ... and y_a, y_b, ... are the importance or weighting factors for the major parameters and subgroup parameters respectively, and the r's represent the instrument's rating values within the subgroup. The sum of the weighting factors in each subgroup and the sum of the weighting factors for each major parameter must each equal 1.0.

and the rating values, gave an indication of the relative degree to which each unit met the desired or required criteria. Even though some factors were not easily quantified, this methodology helped identify those units best suited for the intended application. By imposing a set of minimum acceptable requirements, it was possible that no detector would be judged acceptable or potentially acceptable, although this was not expected based on preliminary discussions with the instrument manufacturers and on an understanding of the technologies involved. Weighting factors of 0.4, 0.4, and 0.2 were assigned to the major parameters of particle sensing, operation, and cost, respectively. It was reasoned that particle sensing and operation requirements were of equal weight because both were needed for an acceptable system. Obviously, a unit with impeccable particle sensing characteristics, but with inadequate potential to meet the operational requirements, would be unacceptable, and vice-versa. Operational and functional ratings were primarily subjective based on determinations from analysis of each unit's potential for meeting a particular requirement. Cost ratings were also somewhat subjective, based on a combination of manufacturer input and our own analysis and assessment.

During one of the quarterly meetings at TACOM (which covered program status, the trade-off study, and the bench set-up for experimental evaluation of the prototype dust detectors), it was emphasized that the top priority (at the time) was to complete the preliminary trade-off study based on information currently on-hand concerning each dust detector's potential performance and on analyses of the specific technologies involved. The philosophy was to document what was known at the time, and to fill in the "blanks" as more information was received and analyzed. Specific areas of concern would also be documented.

Because the dust detectors were essentially prototypes, at least as far as this particular application was concerned, it was necessary to assess both the potential of the technologies involved and the manner in which these technologies were implemented into the instrument. Bench testing evaluation, which TACOM considered a lesser priority at the time, was primarily intended to verify instrument function and operation in terms of ability to check and discriminate road dust as specified in the performance requirement. As such, testing was primarily intended as a supplemental screening tool for verification in conjunction with the initial trade-off study. Test results, when completed, would be used to modify or update the initial trade-off study, as appropriate.

Since a major objective of the trade-off study was to indicate which instruments were most likely to be able to be put on a vehicle, it was important to determine what steps would be required to harden each unit for vehicle integration, and at what cost. Both initial and life-cycle cost factors were considered, as were estimates of the lead time needed to take the prototype from its current state of development to the required hardened state. As a basis for comparison, incremental quantities of 25, 50, and 100,000 units were considered.

Since the area of cost was highly subjective, it was necessary to carefully analyze manufacturer estimates in terms of cost realism and schedule. In order to obtain certain inputs and supporting data for the trade-off study, letters were sent to manufacturers who had either submitted or stated they intended to submit a prototype unit.

Results for the preliminary trade-off study are shown in Table 10. As can be seen, some results for the particle sensing parameters were based on anticipated values while others were based on indications from the preliminary test data. Overall, the study was primarily based on "best" estimates, considering information on hand, in an attempt to quantify potential performance with respect to specific performance and cost parameters. Many of the estimates were derived from discussions with each manufacturer concerning their particular detector and from our analysis of the detector's merits relative to the group. As such, many of the estimates had not been confirmed through laboratory testing (for instance, at this point, the problem of large-term stability for the EXTREL probe had not yet been confirmed) nor by specific documentation, although we were in close contact with each manufacturer and expected supporting data shortly. These data, along with the preliminary bench test data which were to be generated concerning function and operation, would be used to update the trade-off study in an effort to better differentiate among the candidate detectors. Hence, an updated trade-off study was completed with respect to the particle sensing requirements, as shown in Table 11. With exception of the AUBURN and EXTREL units, this study indicated that several candidates showed potential for use as an engine inlet air dust detector. However, it was also clear that several modifications and additional testing were required. In all cases, the first round bench tests seemed to be the first serious exposure of these instruments to the particular dust type and dust distributions that were of interest in this project. In this regard, the preliminary tests were very beneficial in providing the feedback needed to indicate the present level of performance and to suggest the modifications or adjustments needed to better zero in on the required response range.

At this point, the most practical and beneficial next step would be to conduct a second round of tests on the modified instruments, after fully discussing the current results with each instrument manufacturer. It was likely these tests would lead to a definite ranking of the detectors via an updated trade-off study. It was also likely that better cost data and a better modification of each instrument's operational capabilities, based on the modified designs, would be available. As it turned out, cost differentiation was not a major factor. Operational requirements, on the other hand, particularly vehicle interfacing, is an important factor, as discussed later when considering sampling techniques and the in-duct concentration issue.

TABLE 10. PRELIMINARY TRADE-OFF STUDY OF POTENTIAL DUST DETECTORS

Parameters / Manufacturers		Atcor	Auburn International	EXTREL	Monitek	Pacific Scientific	TSI
Technology Employed		Forward light scattering	Tribo-electrification	Surface ionization	Forward light scattering	Forward light scattering	Forward light scattering
Sensor/Duct Interface		Sample with-drawn by probe & sent to sensor	Contact probe in flow stream	Contact probe in flow stream	Scans across flow stream	4	Flow through probe containing sensor inserted in duct
PARTICLE SENSING REQUIREMENTS (dynamic response and function) - Major Parameter Importance Factor = 0.40							
Subgroup Parameter and Importance Parameter							
Response to particle size	(.25)	.25a	.15 i[1]	.20 a[2]	.22 i	4	.22 i
Response to particle concentration	(.25)	.25 a	.15 i[1]	.20 a[2]	.22 i		.20 i
Response time	(.20)	.20 a	.20 i	.20 a	.20 i		.20 i
Stability	(.15)	.12 a	.10 i[1]	.10 a[2]	.12 i		.12 i
Sensitivity to probe[3] alignment, orientation or position	(.15)	.10 a	.15 i	.10 a	.15 i		.10 i
$\sum$	(1.00)	.92	.75	.80	.91		.84
Total weighted score for this major parameter ($\sum$x0.40)	(.400)	.368	.300	.320	.364		.336

COMMENTS/FOOTNOTES

a - anticipated
i - indicated by preliminary test data
1. Sensitivity decreases as dust particles build up on probe.
2. Sensitivity may decrease if dust particles build up on probe.
3. A low number indicates high sensitivity, which is undesirable.
4. Pacific Scientific is still defining instrument since development is being "piggy-backed" on another program which employs a similar technology.

TABLE 10. PRELIMINARY TRADE-OFF STUDY OF POTENTIAL DUST DETECTORS (Continued)

OPERATIONAL REQUIREMENTS - Major Parameter Importance Factor = 0.40							
Vehicle Compatibility	(.40)	.35	.35	.40	.35		.38
Reliability	(.30)	.28	.25	.25	.28		.25
Environmental Resistance	(.20)	.15	.15	.15	.15		.15
Maintainability	(.10)	.08	.07	.08	.09		.09
	$\sum(1.00)$	**.86**	**.82**	**.88**	**.87**		**.87**
Total weighted score for this major parameter ($\sum$x0.40)	(.400)	.344	.328	.352	.348		.348
COST FACTORS - Major Parameter Importance Factor = 0.20							
Life Cycle Cost	(.8)			.6			
Initial Cost	(.2)			.2			
	$\sum(1.0)$			.8			
Total weighted score for this major parameter ($\sum$x0.20)	(0.20)			.16			
TOTAL WEIGHTED SCORE	(1.00)			.832			

TABLE 11. UPDATED PRELIMINARY TRADE-OFF STUDY OF POTENTIAL DUST DETECTORS

Parameters / Manufacturers		Atcor	Auburn International	EXTREL	Monitek	Pacific Scientific	TSI
Technology Employed		Forward light scattering	Tribo-electrification	Surface ionization	Forward light scattering	Forward light scattering	Forward light scattering
Sensor/Duct Interface		Sample with-drawn by probe & sent to sensor	Contact probe in flow stream	Contact probe in flow stream	Scans across flow stream	Sample with-drawn by probe and sent to sensor	Flow through probe containing sensor inserted in duct
PARTICLE SENSING REQUIREMENTS (dynamic response and function) - Major Parameter Importance Factor = 0.40							
Subgroup Parameter and Importance Parameter							
Response to particle size	(.25)	.20	.15 a	.10 a	.20	.20	.20
Response to particle concentration	(.25)	.20	.15 a	.10 a	.20	.20	.20
Response time	(.20)	.20	.10 a	.10 a	.20	.20	.20
Stability	(.15)	.12	.05 a	.05 a	.12	.12	.10
Sensitivity to probe[b] alignment, orientation or position	(.15)	.10	.15	.10	.15	.10	.10
Σ	(1.00)	.82	.60	.45	.87	.82	.80
Total weighted score for this major parameter (Σx0.40)	(.400)	.328	.240	.180	.348	.328	.320

COMMENTS/FOOTNOTES

a Sensitivity decreases as dust particles build up on probe.

b A low number indicates high sensitivity, which is undesirable.

5.5. Laboratory Testing

5.5.1. Overview. Testing was conducted in three stages or rounds. In stage one, preliminary bench testing was accomplished on pre-prototype units to assess feasibility and to determine potential applicability with respect to dust detector requirements and project objectives. Six units were tested in round one: four light scattering (ATCOR, MONITEK, HIAC/ROYCO, and TSI), one surface ionization (EXTREL), and one triboelectric (AUBURN). Specific tests and test results are discussed later in the report.

During first round testing, each unit was evaluated against specific criteria so that a trade-off analysis could be accomplished to rank the units in order of their potential suitability, and to define areas requiring improvement or alteration. The intent was to identify the two or three most promising candidates which, after some modification, would be exposed to more rigorous follow-on testing. It is important to note that the units initially submitted for testing were not specifically designed for automotive dust detector applications. Instead, these units were generally converted prototypes from a more general class of particle detectors that in theory, and because of their special applications or features, indicated a potential for meeting the objectives of the project. Accordingly, first round testing was primarily aimed at assessing function; that is, measuring detector response to specific dust environments on both an instantaneous and long-term basis.

Units undergoing second round testing included ATCOR, MONITEK, and HIAC/ROYCO, and one new unit (MET-ONE) that was submitted late in the program, but which indicated sufficient potential to warrant testing. The AUBURN and EXTREL units were dropped from the program because their technology proved inadequate for long-term vehicle applications and because neither manufacturer chose to submit a refined prototype. The TSI unit was dropped at TSI and TACOM's request, since a TSI upgrade was being developed separately under another TACOM project.

Following second round testing, the ATCOR, MET-ONE, and HIAC/ROYCO units were subjected to a full-scale laboratory test on a mocked-up 5-ton truck air cleaner system. The MONITEK unit was not included because certain difficulties encountered with the second round prototype could not be corrected in time for the third round (full-scale) test. For full-scale testing, an actual 5-ton truck air cleaner system, from the air inlet through the engine intake manifold, was installed on a standard laboratory filter test stand that filtration performance could be monitored during the overall evaluation. In this manner, the performance of each dust detector could be measured and evaluated throughout an entire filter test under exposure to a variety of simulated field conditions, including normal operation under high inlet dust concentration levels, as well as operation under conditions simulating specific (induced) air cleaner faults. This test was significant because it exposed the dust detectors very nearly to the actual flow streams (for this particular vehicle) likely

to be encountered in field operation under both full-load and dynamic vehicle operation. Dynamic airflows in direct response to accelerations, decelerations and such were not specifically simulated, although operation to a variable flow schedule was conducted during part of the test. Data taken during numerous start-ups and shut-downs showed some sensitivity to transients (for some instruments) even though one of the objectives is to "down play" transient responses to avoid false triggering, as already discussed. Results from the full-scale tests are particularly interesting because they provide correlation among actual filter efficiency, downstream particle size and concentration levels as a function of filter dust loading, and instrument response. Furthermore, the results were obtained under a well-controlled laboratory environment using typical military filter test procedures, while exposing the instruments to a series of realistic (simulated), operating conditions.

5.5.2. Bench Testing. During the course of the project, several series of bench tests were conducted both to measure filter performance for typical military air cleaner systems and to evaluate dust detector performance and potential. These tests are described below.

5.5.2.1. Filter Testing. Early in the project, testing was accomplished to assess filter performance for three different military air cleaner systems as a function of dust loading and upstream dust exposure under normal and abnormal filter conditions. In particular, data were sought to quantify the downstream environment in terms of particle size distribution and concentration level.

This is important because almost all automotive and industrial air filters are known to experience an increase in particle removal efficiency over time as the filter elements load with dust. In fact, laboratory tests have clearly shown that both the amount and size of the particles penetrating the filter decrease as the filter loads with dust (until sufficient dust is captured to cause particle migration and reentrainment under very high pressure drops) while fractional and overall efficiency increase. This means that a new (clean) air filter element is inherently less efficient and therefore passes significantly more dust, even under normal filter operation than an in-service filter which has undergone some degree of dust loading. This is true even for filters which have shown high average or overall laboratory efficiencies. Furthermore, in the case where the filter is protecting an engine, the dust remains in the engine much longer than if the dust were passed at the steady rate suggested by the average for overall efficiency data. In addition, dust ingestion has an immediate and major effect on engine wear, and causes significant carry-over wear even when dust is no longer being ingested.

Respecification of the filter element's initial efficiency requirement could help correct this problem; however, this is not likely to occur because it would probably have an adverse impact on service life. One can expect, therefore, that air filter elements used to protect engines on military vehicles will allow significant particle penetration when operating in

highly dusty environments, even when operating properly. For this reason, the dust detector must meet very stringent triggering requirements so as not to trigger during "normal" system operation and yet remain sensitive enough to trigger at the onset of "abnormal" filter operation. Furthermore, it means that equipment used in the dust detector system will have to function in dusty environments, even during normal filter operation, and if they are not designed properly, this could degrade their performance over time.

The general features of the test arrangement are shown in Figure 5-27. During testing, the amount of dust penetrating the test filter is determined on a mass basis by measuring the weight gain of the downstream absolute filter. While particle size determinations are not usually made during normal air filter tests, the mass of dust trapped by the absolute filter is an indication of the amount of dust that will eventually enter the engine, and in tests where incremental efficiencies are measured, the data have shown that the majority of dust penetrates early during the test. As discussed in detail in 5.2.1, particle size measurements were made to characterize the downstream flows as a function of filter dust loading, and these data served, in large measure, as the basis for establishing the triggering criteria. The particle sizing instrumentation employed is discussed in 5.5.2.2, and the method of data analyses for both the filter tests and the dust detector evaluations is discussed in 5.5.2.3. In effect, the downstream particle size data were analyzed in terms of number and mass concentration as a function of particle size and the degree of filter loading. These data were evaluated for each sampling run, then monitored on a run-to-run basis, and finally, consolidated to show test-to-test efficiency. Efficiency values calculated from the particle size distributions tended to compare favorably with experimental incremental and cumulative results. The shift in the data with dust loading (service life) was clearly evident. As expected, when the filter loaded with dust (as ΔP increased), both the number and mass of downstream particles decreased. In addition, subsequent particle size distributions steadily decreased, while incremental efficiencies increased.

It should be noted, however, that the dust detector must operate satisfactorily during the full lifetime of the filter element, hence the threshold values must be set to be insensitive to the downstream performance parameters of the clean filter element. This is an important realization because it means that the dust detector must tolerate the potentially large concentration levels present immediately after a new filter element(s) is installed, and still be able to discriminate when a faulty condition occurs.

5.5.2.2. Particle Sizing Instrumentation; Laboratory Standard. During almost all testing (filter, first and second round bench, and the full-scale 5-ton truck mock-up), measurements of particle size were the major test parameters. For the filter tests, these measurements, taken collectively, provided the basis for determining the downstream distributions needed to quantify the dust detector triggering criteria. For the bench tests,

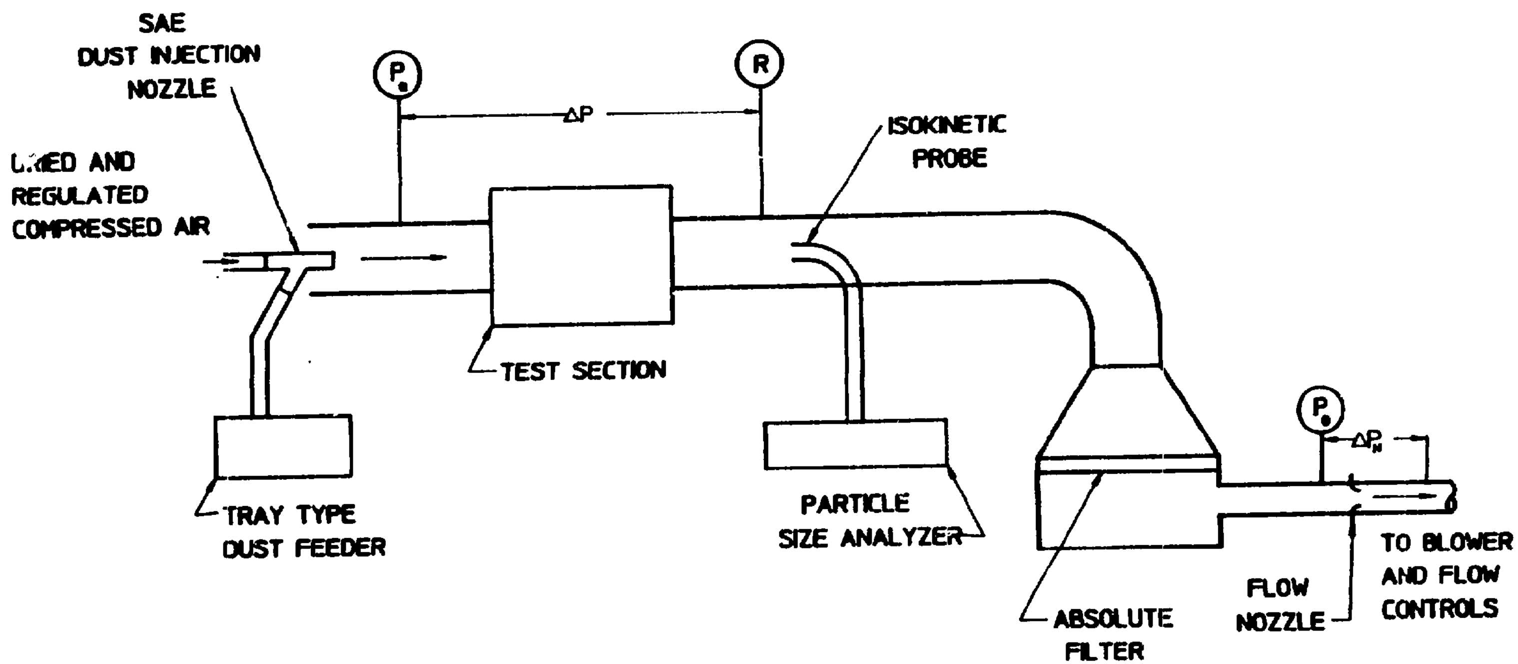


FIGURE 5-27. LABORATORY ARRANGEMENT FOR TESTING 2-TON AND 5-TON TRUCK AND M2/M3 FILTER ELEMENTS

particle size measurements were used to both set specific stream conditions and to judge instrument response. For the full-scale test, the downstream particle size measurements served to monitor both filter performance and dust detector response under simulated, real-life flow conditions and dust environments.

In all of these tests, the laboratory standard for particle sizing was a HIAC/ROYCO 4102 particle size analyzer consisting of a 4100 counter and 1200 white light scattering sensor. This unit was selected because it was known to respond well to non-spherical, poly-dispersed, natural dust, and therefore was likely to respond well to the dust distributions of interest in this project (for instance, the lower end of the AC Fine size range; less than 20μm). It was also likely that the 4102's response to the test dust would be closely compatible with its response to the monodispersed latex spheres which are typically used during instrument calibration. Furthermore, the 1200 sensor had an advertised acceptance range of 100 million particles per cubic foot air, well above the expected range of the study. In practice, this limit was more on the order of 1.3 million particles per cubic foot, which was still acceptable although some data would over-concentrate for large concentrations of the smallest particle sizes. As the project progressed and the particle size range of interest was defined to be in the 3μm and above range, the HIAC's range settings were adjusted upward and the overconcentration problem became less of a nuisance. The suitability of the HIAC was investigated periodically by comparing mass value as calculated from the HIAC data with mass particle size values as determined by an Andersen Cascade Impactor operating on the same flow. Overall, the degree of correlation was very close, particularly in the area of interest, the 3-10μm range.

5.5.2.3. Particle Sizes dp_1 and dp_2. For making calculations and plotting results, the geometric mean diameter and a modified mean diameter (for truncated log normal distributions) were determined for the six particle size ranges set in the particle size analyzer. The total concentration of particles present was allocated to six particle size intervals with the maximum combined range covering sizes from 0.5 to 20μm. The geometric mean diameter for each interval was calculated as

$$dp_1 = 10^{(\log x_1 + \log x_2)/2} \tag{6}$$

where x_1 and x_2 were the lower and upper boundaries of the size intervals, respectively. The use of equation (6) assumed that the particles of interest were distributed log-normally, a distribution which often represents airborne particles in the range of interest and more importantly, is fairly well represented by the test dust used to evaluate military air cleaner systems and often for the study of dust in and around military vehicles. Although the test particles were not spherical, sphericity was assumed in all calculations, particularly when converting from particle number to particle mass.

The second diameter, termed the modified mean diameter, was calculated as

$$\left(dp_{2_{30}}\right)^3 = \frac{\Sigma_i d_i^3}{\Sigma_k N_k} = \Sigma_k \frac{\left(d_{ku}^4 - k_{kl}^4\right) N_k}{\left(d_{ku} - d_{kl}\right) x\ 4} \ / \ \Sigma_k N_k \tag{7}$$

which reduces to

$$dp_2 = \sqrt[3]{(x_1 + x_2)(x_1^2 + x_2^2)\ /4} \tag{8}$$

where x_1 and x_2 are as defined previously. dp_1 and dp_2, for the general ranges of interest in this project, are given in Table 12 and plotted in Figure 5-28. As can be seen, the modified particle diameter is shifted from the geometric midpoint to give slightly higher values in all size ranges. As Equations 7 and 8 show, dp_2 is a volume mean diameter for spherical particles contained in a range having upper and lower bounds ku and kl. The impact of dp_1 and dp_2 on volume or mass (for the x_1 to x_2 intervals chosen), assuming spherical particles, is illustrated in Figure 5-29. While specific ratios of M_2 to M_1 and dp_2 to dp_1 depend on the specific intervals (x_1 to x_2) chosen, the trend is generally decreasing with increasing particle size where x_1 to x_2 covered smaller particle size intervals.

The log normal distribution is typically used to represent dust distributions because it fits the empirical data well and because it's mathematical form is well known and convenient for dealing with the weighted distributions presented by most dust. However, although useful, this distribution does not have a theoretical basis for applications to airborne dust.

In particle sizing work, the log normal distribution is normal with respect to the logarithm of the particle diameter. Therefore, to normalize the test data, the frequency data (number or mass) were divided by the difference in the logs for the interval of interest, $\Delta\log dp = \log d_2 - \log d_1$. (Since all weighted distributions of any log normal distribution will be log normal, and have the same geometric standard deviation, they will have the same shape when plotted on a logarithmic scale, as illustrated in Figure 5-30. The data presented elsewhere in this report, for corresponding tests, have this relationship). Drawing a smooth curve through the rectangular tops of the histograms corresponding to each range set on the particle size analyzer gave particle size distribution curves which were amenable to both mathematical and graphical interpretation. Before plotting, these distributions were converted to show concentration. Many of the curves presented in this report, were developed in this manner.

The only difference from conventional practice is that in some cases, the data for each interval were plotted at a slightly modified "mid-point" (dp_2) rather than at the true log mid-point (dp_1) for each interval. The reason for doing this, as already noted, was because we were working with truncated distributions caused by the use of air filters or to the

TABLE 12. PARTICLE SIZE PARAMETERS AS A FUNCTION OF PARTICLE SIZE RANGE x_1 TO x_2

Range, x_1 to x_2, μm	dp_1, μm	x_1 to x_2	dp_2, μm	dp_2/dp_1	Γ*
0.5 - 1.5	0.866	3.0	1.08	1.247	1.940
1.5- 3	2.12	2.0	2.33	1.099	1.328
3 - 5	3.87	1.67	4.08	1.054	1.172
5 -10	7.07	2.0	7.77	1.099	1.328
10 - 15	12.2	1.5	12.7	1.041	1.128
>15 (15-20)	17.3	1.33	17.6	1.017	1.053
3 - 5	3.87	1.67	4.08	1.075	1.172
5 - 7	5.92	1.40	6.06	1.024	1.073
7 - 9	7.94	1.29	8.04	1.013	1.038
9 -11	9.95	1.22	10.0	1.005	1.015
11-15	12.8	1.36	13.1	1.023	1.072
>15 (15-20)	17.3	1.33	17.6	1.017	1.053

* M_2/M_1 or V_2/V_1, assuming spherical particles

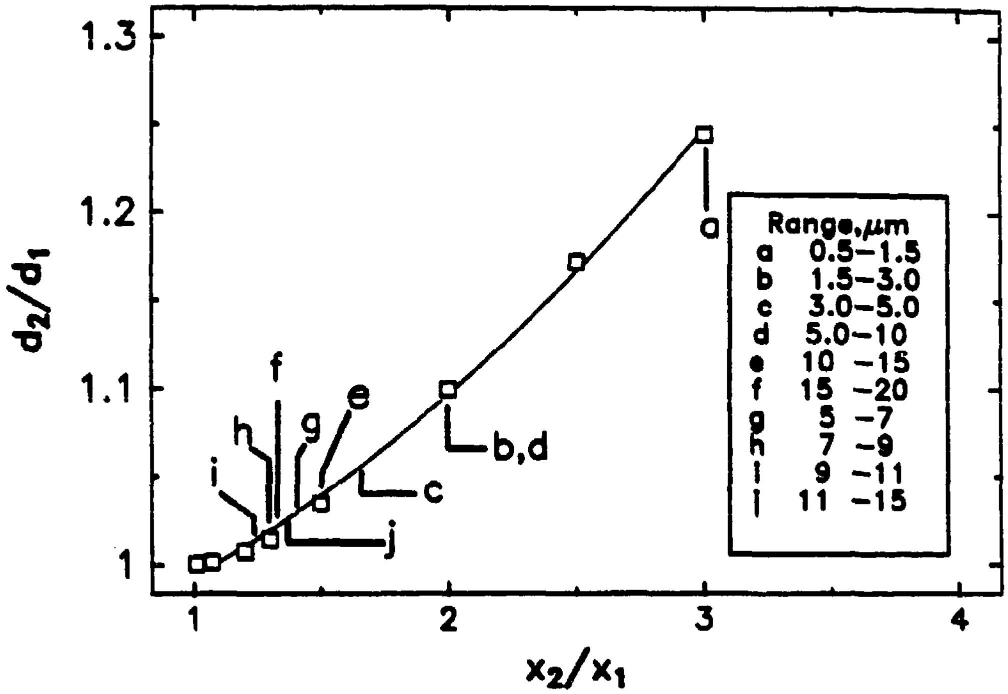


FIGURE 5-28. dp_1 AND dp_2 AS FUNCTION OF PARTICLE SIZE RANGE, x_1 AND x_2

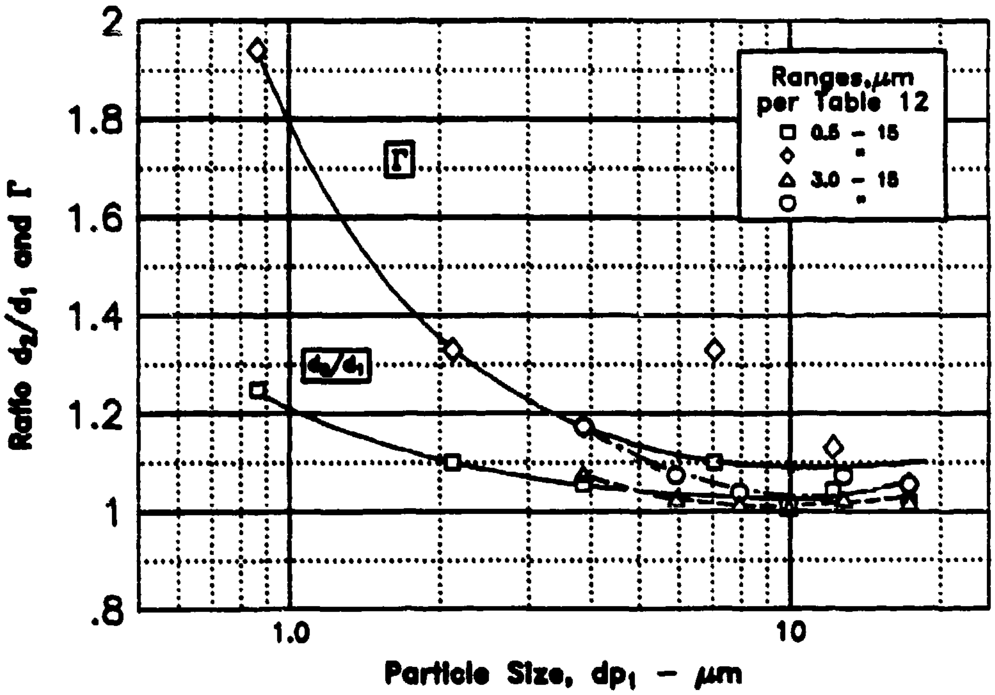


FIGURE 5-29. IMPACT OF dp_1 AND dp_2 ON PARTICLE VOLUME AND MASS

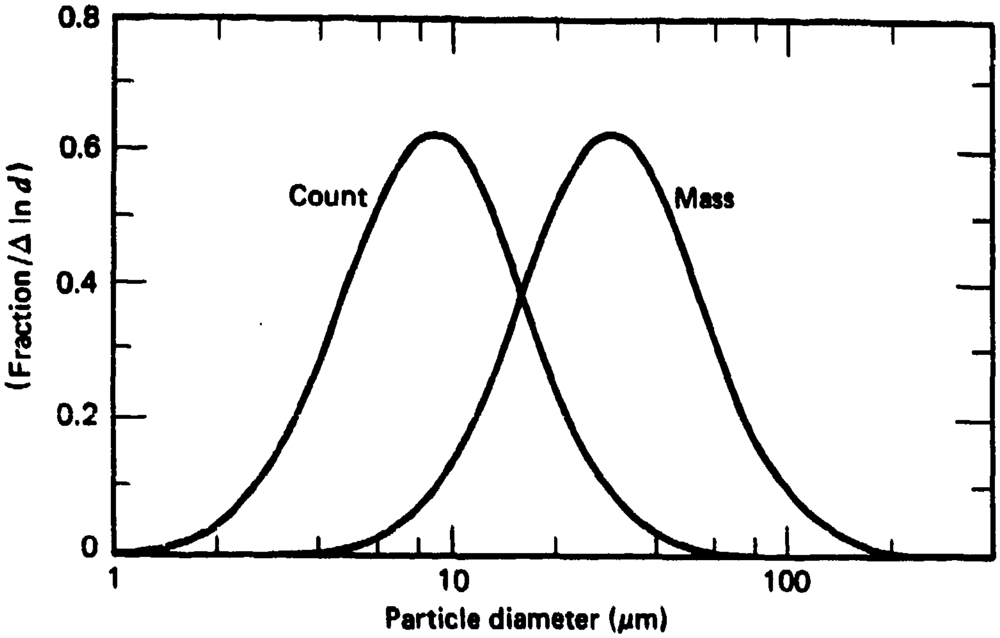


FIGURE 5-30. ILLUSTRATION OF WEIGHTED DISTRIBUTIONS FROM SAME LOGNORMAL DISTRIBUTION; NUMBER AND MASS (LOGARITHMIC SIZE SCALE)

feeding of discrete ranges of dust (rather than with the normal, undisturbed dust distribution). In these situations, it has been found that the data are more representative if the interval particle size diameter is slightly shifted, based on the equation developed for dp_2, which in effect, modifies the log normal distribution slightly to account for the artificial truncation. For example, in the interval of .5 to 1.5μm, the modified mid-point is 1.08μm instead of 0.87μm as it would be by equation (1), or 1.0μm as it would be if calculated arithmetically. In the interval of 10 to 15μm, the comparison is 12.7μm to 12.2μm.

As it turned out, distributions based on dp_2 were used early in the program and in the determination of the initial triggering criteria, whereas similar distributions based on dp_1 were generally used later in the program for comparison of second round bench test data and for analysis of the 5-ton truck test data. While these distributions served to compare the performance of various dust detectors with respect to the laboratory standard, it became apparent later in the program that, since the criteria were based on exceeding specific particle sizes and concentration levels, distributions based on cumulative concentrations would be more direct and useful.

5.5.2.4. Dust Detector Testing; Bench Arrangement. The bench tests were part of a parametric evaluation to determine dust detector potential. Instrument response was measured in a series of tests which provided a wide range of exposure to particle sizes and

concentration levels, and compared the response of the candidate detector to the response of the laboratory standard.

First and second round evaluations were conducted using a laboratory bench set-up, as shown in Figures 5-31, 5-32 and 5-33. During operation, dust was fed into a vertical inlet tube, then through a variable flow precleaner, followed by an upstream filter section. The filter section could house various foams or meshes, a small pleated panel, or a combination of these. With this arrangement, and with control over precleaner scavenge flow and the rate of dust ingestion, the particle size distribution and concentration level introduced to the dust detector could be tailored to meet desired conditions.

Dust feeding was initiated with an air-floated dust feeder, which worked well for this application because it helped fractionate the dust particles so as to reduce the number of large particles introduced into the test loop. This reduced the burden on the precleaner and on the cut-off filters. Immediately downstream of the test section, an isokinetic sample was withdrawn from the test duct for evaluation on the HIAC analyzer, which served as the laboratory standard for characterizing the downstream particle distributions. The test bench could easily be adjusted for flow rate so that specific velocities could be presented to the test section. In addition, several test sections could be interchanged to accommodate different test units and to apply various geometric configurations.

During testing, particular care was taken in positioning all sampling probes, focal points, and such to assure that like samples were being examined by the detector(s) and the standard at any given time. In addition, for detectors which withdrew a sample for analysis, as well as for the HIAC, care was taken to provide isokinetic sampling from the primary flow stream with minimal losses from dispersion and fall-out during transport to the sensor.

The test bench was calibrated to present controlled dust environments to the test probes in order to measure their response under simulated operation. For the most part, the test bench simulated the full-scale air cleaner test unit under both normal and induced fault operation. Downstream particle size and concentration distributions could be adjusted to measure response above and below the recommended threshold (triggering) level.

For the most part, analyses of round one and round two data were accomplished by measuring the instrument's dynamic response to a variety of dust concentration levels as measured by the HIAC 4102 particle size analyzer. Specifically, the instrument's response to specific dust distributions and to changes between distributions was noted. Comparisons during first round testing were made using the normalized concentration data ($\Delta N/\Delta \log dp$) as discussed earlier. Analyses during much of the second round testing and for all of

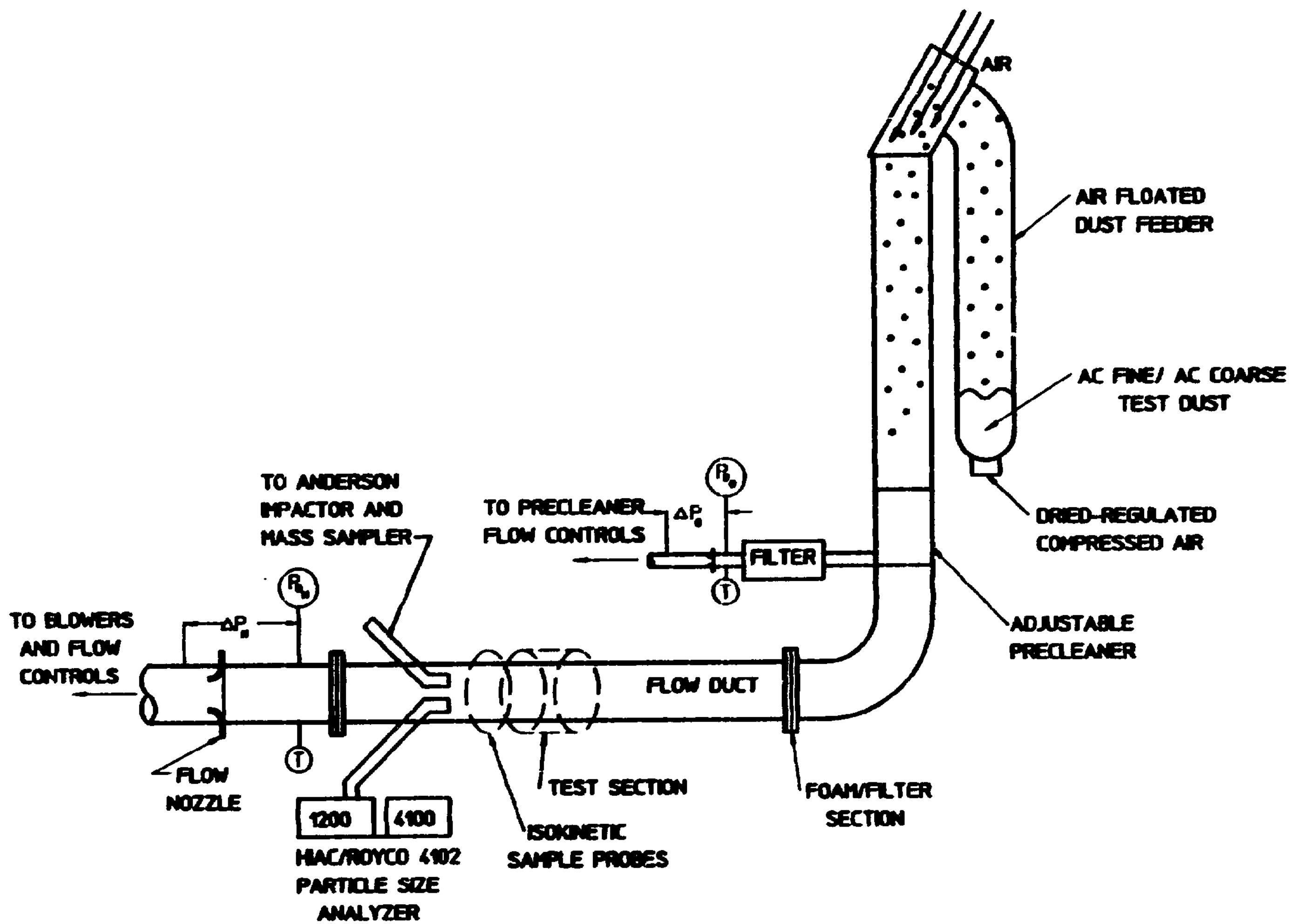


FIGURE 5-31. SCHEMATIC OF BENCH TEST SET-UP FOR FIRST AND SECOND ROUND TESTING

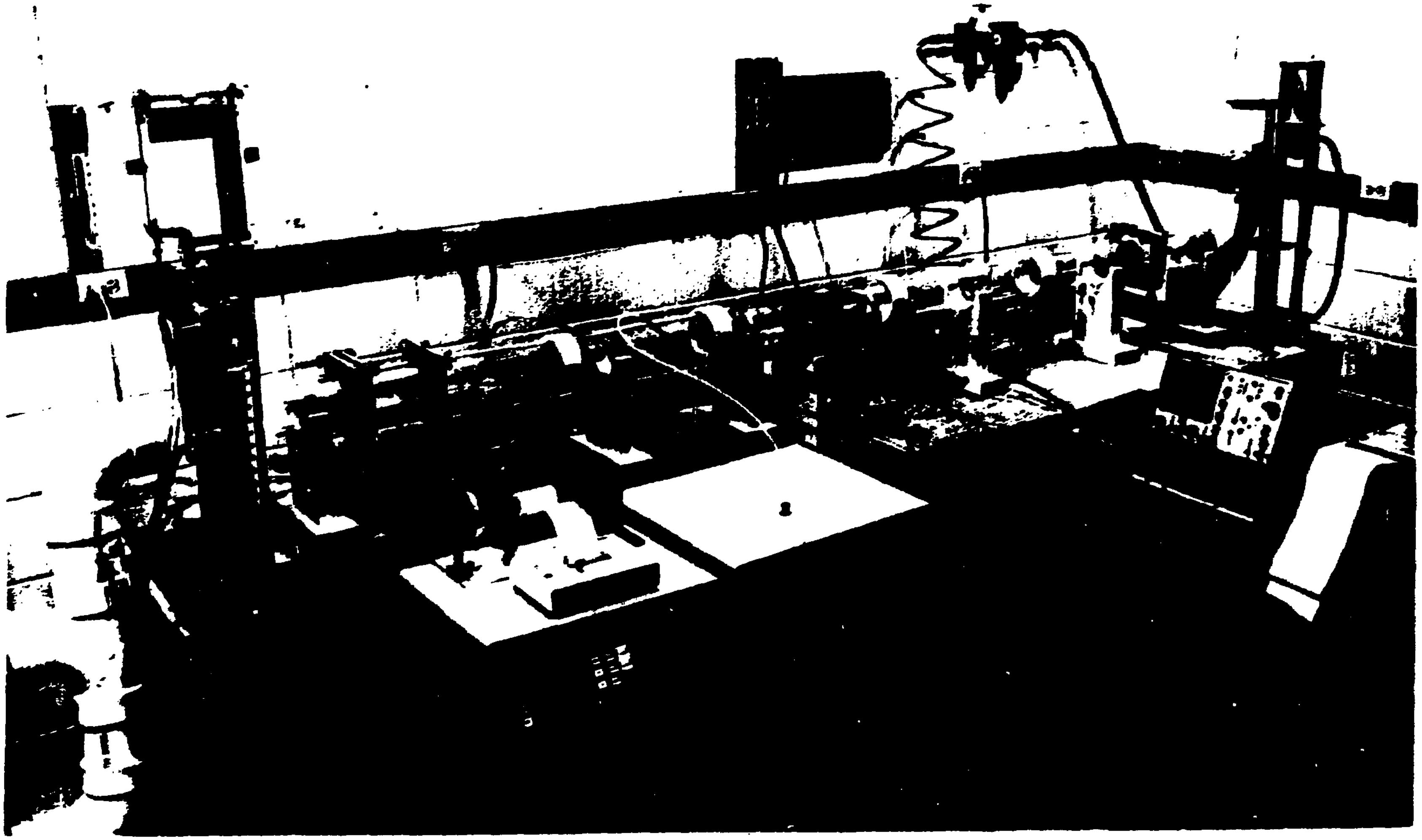


FIGURE 5-32. LABORATORY BENCH SET-UP USED FOR FIRST AND SECOND ROUND TESTING (HIAC/ROYCO SECOND ROUND PROTOTYPE UNDER TEST)

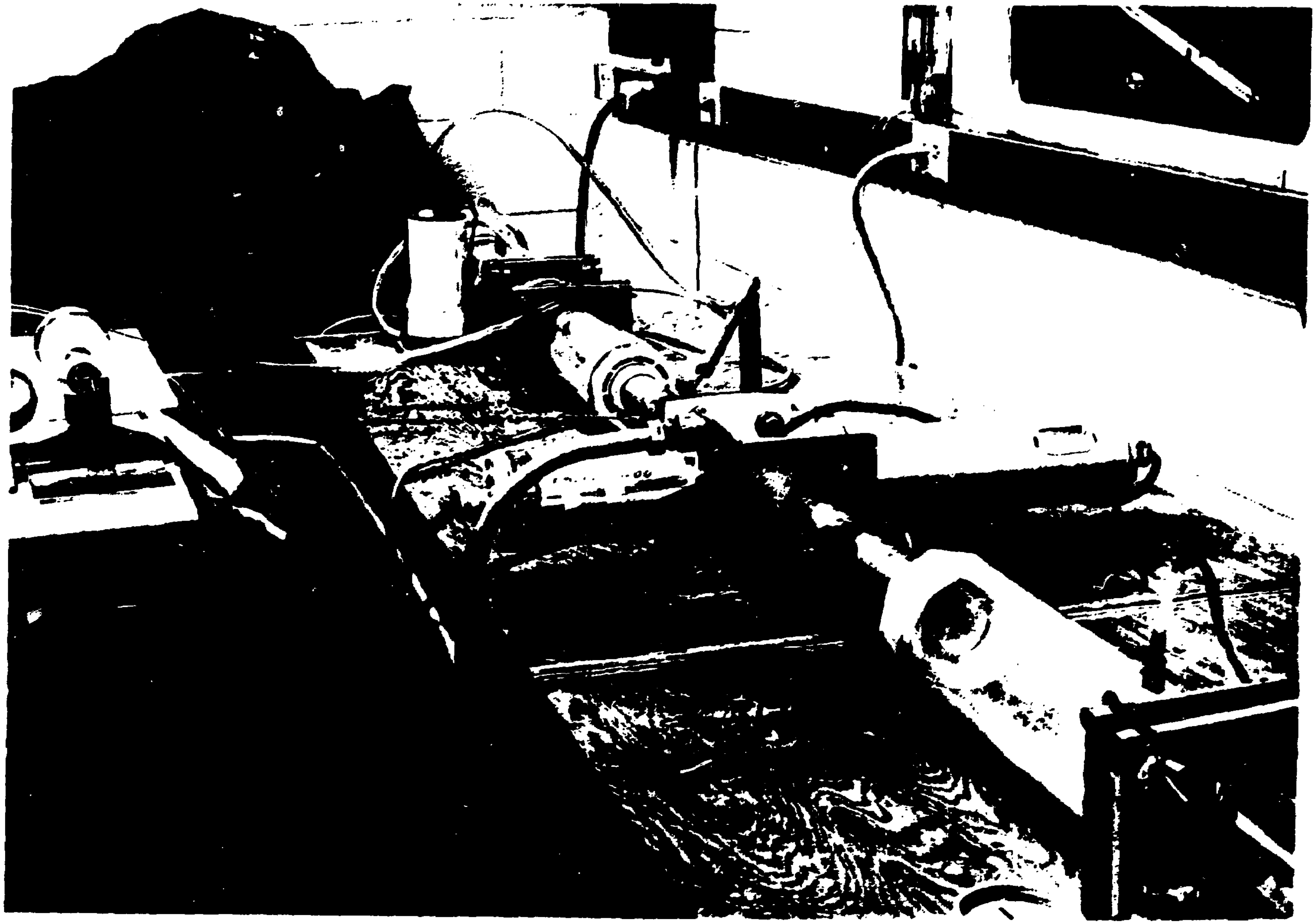


FIGURE 5-33. LABORATORY BENCH SET-UP USED FOR FIRST AND SECOND ROUND TESTING (FIRST ROUND AUBURN - FOREGROUND - AND MONITEK UNITS UNDER TEST)

the 5-ton truck testing, were generally completed using the cumulative number concentration data and either measuring directly, where possible, or estimating, where necessary, the sensor's output for particles greater than 7μm. As discussed in more detail below, the specific analysis method used was altered to accommodate the sensing methodology employed for a given dust detector.

5.5.2.5. Representative Sampling; Implications of Internal and External Sensing. It is quite obvious that meaningful particle size and concentration measurements must start, at the very least, with examination of a representative (in-duct) sample. This requirement, however, is not trivial for an automotive dust detector because the engine's air induction-tubing and variable operating air flows are not conducive to either in-situ or extractive (sampling) interrogation. Even under favorable conditions, particle sensing in disturbed flows can be a complex phenomenon involving aerodynamic turbulence and local aberrations. This complexity increases when difficult geometries and rapidly varying flows are common. Therefore, the process implications of internal and external sensing were evaluated. Here, by definition, internal sensing is accomplished when the sample is analyzed at the point of sampling; for instance, within the air inlet duct between the filter and the engine, whereas external sensing involves withdrawing the sample from the duct and transferring it, usually through a small tube, to an externally located sensor for on-line analysis. This distinction is easily illustrated by the dust detectors investigated in this project. For example, the AUBURN, EXTREL, HIAC/ROYCO, and TSI detectors each had their sensing zone located within the duct and made the measurement at the point of sampling. Conversely, the ATCOR and MET-ONE units, as well as the HIAC, pulled a continuous sample from within the duct and transported it via small diameter tubing to a remote sensor for analysis.

Each strategy, internal sensing at the point of sampling and external at a remote sensor, has its advantages and disadvantages. For example, for internal sampling and sensing, it is necessary to physically locate the sensor in the duct or at the duct surface, a requirement that can create interfacing problems due to space and configuration limitations, adverse shock and temperature environments, and routine and unscheduled maintenance needs. Conversely, externally located sensors, which only require a sampling probe in order to interface with the duct, avoid many of these problems since the detector sensing zone can often be much more conveniently located. Remote sensing, however, requires particle sampling and transport, and both can reduce data quality and thereby misstate the true in-situ environment.

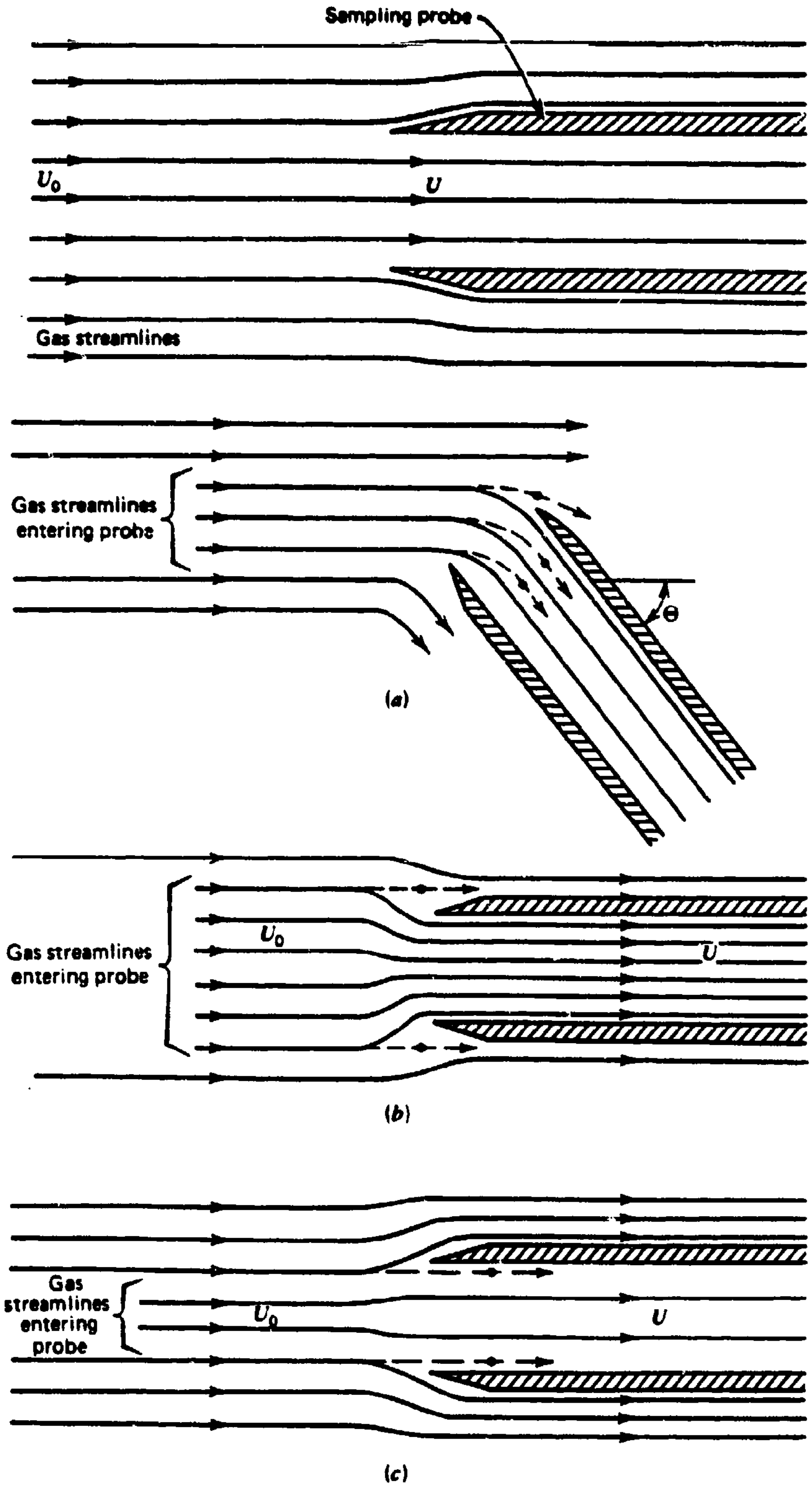
External sampling devices depend in an essential way on both effective sampling and efficient particle transport. It is easy to see that in order to accurately measure the size and concentration of the particles in the duct, it is first necessary to obtain a representative sample and transport it unaltered to the sensing zone. This requirement is independent

of the sensor and is a requirement for all remotely located sensors. Clearly, even if the external sensor works perfectly, its interpretation of in-duct particles will only be as good as the integrity of the sample arriving at the sensor. For this reason, it is important to analyze potential errors that can result from improper sampling and/or transport. As will be shown, the particle size distributions and concentration levels at the sensor can be significantly distorted by non-representative sampling and by the deposition of particles in the sampling lines enroute to the remote sensor. This is particularly true in the non-laboratory, vehicle environment.

In order to obtain a representative sample from a moving flow stream, one that will accurately reflect the true concentration and particle size distribution of the particles in the stream, it is first necessary to extract the sample under isokinetic conditions. This places at least two important constraints on the sampling system, namely that the sampler's inlet be aligned parallel to the gas streamlines, and that the gas velocity entering the probe be identical to the flowing stream velocity approaching the inlet. Under these conditions, all particles approaching the probe, and only those particles, will enter it. Hence, there is no particle loss or gain at the inlet regardless of particle size or inertia. This assures that the concentration and size distributions of the particles entering the sampling tube will be the same as those in the flowing stream at the point of measurement.

While it is easy to see that probe misalignment can cause significant particle sizing errors, it is less obvious that non-isokinetic sampling can also lead to a misrepresentation of particle size and concentration. Nevertheless, errors due to non-isokinetic sampling can greatly distort the particle size distribution and misrepresent the particle concentration level. This is due to particle inertia effects in the region of the curved streamlines near the tube inlet, which, depending on specific flow conditions (underflow or overflow) can cause the ensuing sample to contain an excess or deficiency of larger particles with respect to the actual particle distribution within the flowing stream.

Non-isokinetic sampling, including probe misalignment, is illustrated in Figure 5-34. When the velocity in the probe exceeds the stream velocity, the streamlines are forced to con-converge at the entrance, such that a disproportionate share of smaller particles are pulled into the probe while the corresponding group of larger particles cross the streamlines and do not enter the probe. Since the particles with high inertia are lost from the sample, the sample flow will underestimate the true concentration, particularly with respect to the larger particles. Conversely, when the velocity entering the sampling probe is less than that of the flow stream, the streamlines diverge at the inlet so that some of the larger particles, that were not originally in the gas volume being sampled, travel into the probe. Figures 5-35 and 5-36, after Hinds[7], illustrate these situations. Figure 5-35 shows the effect of the velocity mismatch on the concentration ratio, C/Co, as a function of the square root



Isokinetic Sampling

$U = U_o$

Non-Isokinetic Sampling

a. $\Theta \neq 0$
b. $U \geq U_o$
c. $U \leq U_o$

FIGURE 5-34. ILLUSTRATION OF ISOKINETIC AND NON-ISOKINETIC SAMPLING, INCLUDING PROBE MISALIGNMENT (AFTER HINDS[7])

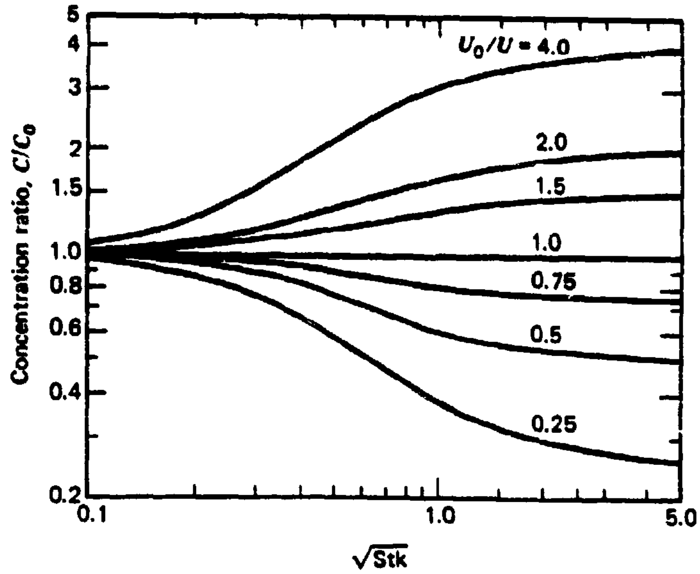


FIGURE 5-35. CONCENTRATION RATIO VERSUS SQUARE ROOT OF STOKES NUMBER FOR SEVERAL VELOCITY RATIOS WITH PERFECT PROBE ALIGNMENT ($\ominus = 0°$)[7]

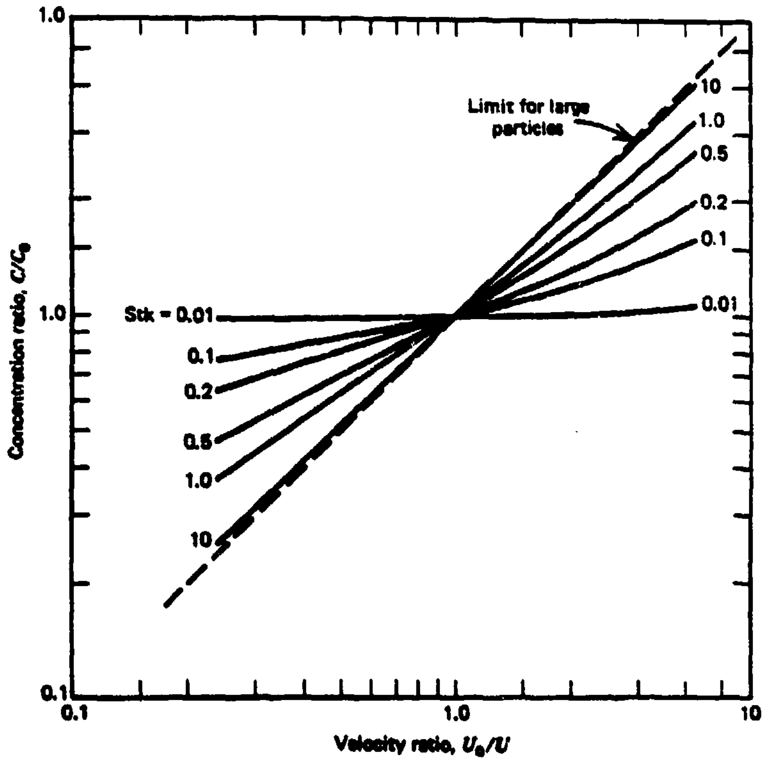


FIGURE 5-36. EFFECT OF VELOCITY RATIO ON CONCENTRATION RATIO FOR SEVERAL VALUES OF STOKES NUMBER, WITH PERFECT PROBE ALIGNMENT ($\ominus = 0°$)[7]

of Stokes number, $\sqrt{\Psi}$, which is directly proportional to particle size. Figure 5-36 restates this information, with the concentration ratio plotted as a function of the velocity ratio for various values of Stokes number. While the first figure shows the impact on concentration as a function of the velocity ratio, for a given Stokes number or particle size, the second figure clearly shows how the concentration ratio is either overstated or understated, particularly for the larger particles (larger Stokes number), as the velocity is over or undermatched. Both figures assume perfect probe alignment ($\Theta=0$) with respect to the main flow streamlines.

The impact of probe misalignment on the concentration ratio is shown in Figure 5-37, where the curves clearly show the importance of probe alignment, which in all cases understates the actual concentration for the larger particles. This is very significant to the dust detector project because it places a stringent requirement on interfacing the sampling probe with the vehicle inlet air duct, for those detectors which require extractive sampling.

It should be noted that representative isokinetic sampling further assumes that the velocity profile is well-defined and known, and that the concentration profile is not skewed from the velocity profile. These conditions are difficult to assure from vehicle type to vehicle type, or even for the same vehicle during different stages of engine and vehicle operation. Requirements of probe orientation and isokinetic sampling place stringent limitations on probe location and arrangement, and this is likely to complicate interfacing the sampling probe with the duct. Furthermore, isokinetic sampling and proper probe alignment only assure a reasonable chance that the concentration and size distribution of the particles entering the probe are the same as those in the main stream. These conditions in no way assure that there will not be particle losses between the inlet and the sensor. Therefore, particle transport, that is the movement of the particle from the sampling probe entrance to the sensor, must also be carefully evaluated, and the impact of errors due to a potential loss of particles to the sampling walls must also be taken into account.

In-situ sensors, that is, sensors which actually measure particle size and concentration level in the duct, are also subject to localized flow conditions. These sensors, however, are not subject to the additional requirements and sensitivities of sample extraction and transport. While it is possible for both approaches to work if implemented properly, there is little doubt that the high level of sensitivity associated with sampling and transport is definitely a major concern in pursuing remote sensing strategies.

In addition to the potential sampling and transport problems mentioned above, external samplers must often contend with another problem because they usually operate at a constant, fixed sampling flow rate. As such, results from these instruments do not provide an accurate representation of the dust concentration in the duct, unless the sampling flow rate just happens to match the duct flow rate, or unless some means is provided to correct

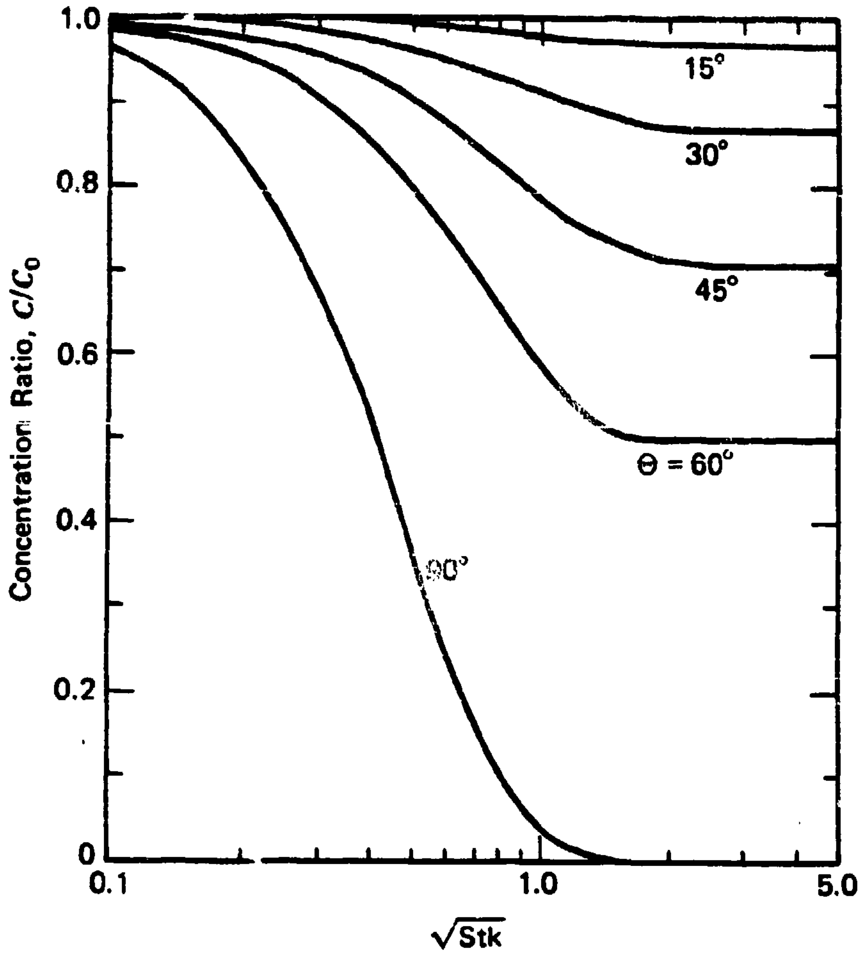


FIGURE 5-37. EFFECT OF PROBE MISALIGNMENT ON CONCENTRATION RATIO, FOR ISOKINETIC SAMPLING[7]

the data for differences in flow. In order to relate the sample data to the concentration value at the point of measurement in the duct, the instantaneous volumetric flow rate in the duct must be known. Since air flows vary with vehicle duty cycle, the data from a constant volume sampler must be corrected to reflect concentrations with respect to in-duct air flows.

The constant volume samplers evaluated in this project, the ATCOR and MET-ONE, gave concentration in terms of the sampler's air flow rate rather than in terms of the in-duct, instantaneous flow, except for the singular case where isokinetic sampling was maintained and the velocity and concentration profiles were relatively well-behaved and defined at the point of sampling. Isokineticity will not be the norm for an operating vehicle because the in-duct air flow will vary with vehicle operation, while the sampling rate and probe diameter will likely remain fixed. This creates two problems: 1) the non-isokinetic sampling conditions will likely lead to errors in the number and size of particles that are actually sampled compared to number and size that would be sampled under isokinetic

(ideal) conditions; and 2) the sampler concentration data will not relate directly to the instantaneous, in-duct concentration data for all vehicle operating conditions. Both problems could be solved mechanically either by measuring the instantaneous in-duct air flow and adjusting the sampler flow to maintain isokinetic conditions at the probe, or by varying the probe tip diameter to maintain isokineticity, although this approach would not be easy to accomplish or lend itself to most practical applications.

With external samplers, there is also the question of particle transport efficiency and this must be considered for both variable and constant rate sampling. Without elaborating at this time, it can be concluded that variable rate sampling is likely to complicate the particle transport issue.

If non-isokinetic sampling errors can be tolerated, then in-duct concentration levels could be calculated from sampler concentration values by employing correction factors based on the ratio of the in-duct to the sampler flow rates. This could be done by measuring in-duct velocity or mass flow using current sensor technology and electronically correcting sampler values prior to comparison with the triggering criteria.

Another major concern was the impact of duct configuration and probe/sensor placement on sensor response, particularly in the context of TACOM's desire to develop a "universal" dust detector for "all" Army vehicles. This concern was investigated both experimentally and theoretically. For example, during testing of some 2½-ton truck elements, the effect of duct shape and probe location was investigated using the duct configurations shown in Figure 5-38, with probes located as shown in Figure 5-39. The results experimentally confirmed our (theoretical) suspicions by showing variety in particle size and concentration with duct shape and probe location.

The subject of dust location and probe/sensor placement was also studied by others closely associated with the project. During a meeting at ATCOR to review their dust detector, Dr. Bardina offered to look at potential particle distributions across a duct for several inlet conditions using a computer program developed by NASA for combustion research. This program modeled particle flows under turbulent conditions and provided a good (preliminary) simulation to illustrate the problem.

Dr. Bardina's analysis for three inlet conditions is presented in Appendix A. Three sampling scenarios are examined: a single probe in the middle of the duct, dual probes equal distances from the centerline (at r/3), and triple probes equally distributed across the duct diameter (at centerline and r/2). Correlation is examined by looking at the particles that would be withdrawn at the specified sampling point(s) compared to the relative particle density expected in the duct, as a function of duct geometry, probe location, and the air flow velocity profile. Results are based on calculation of a non-

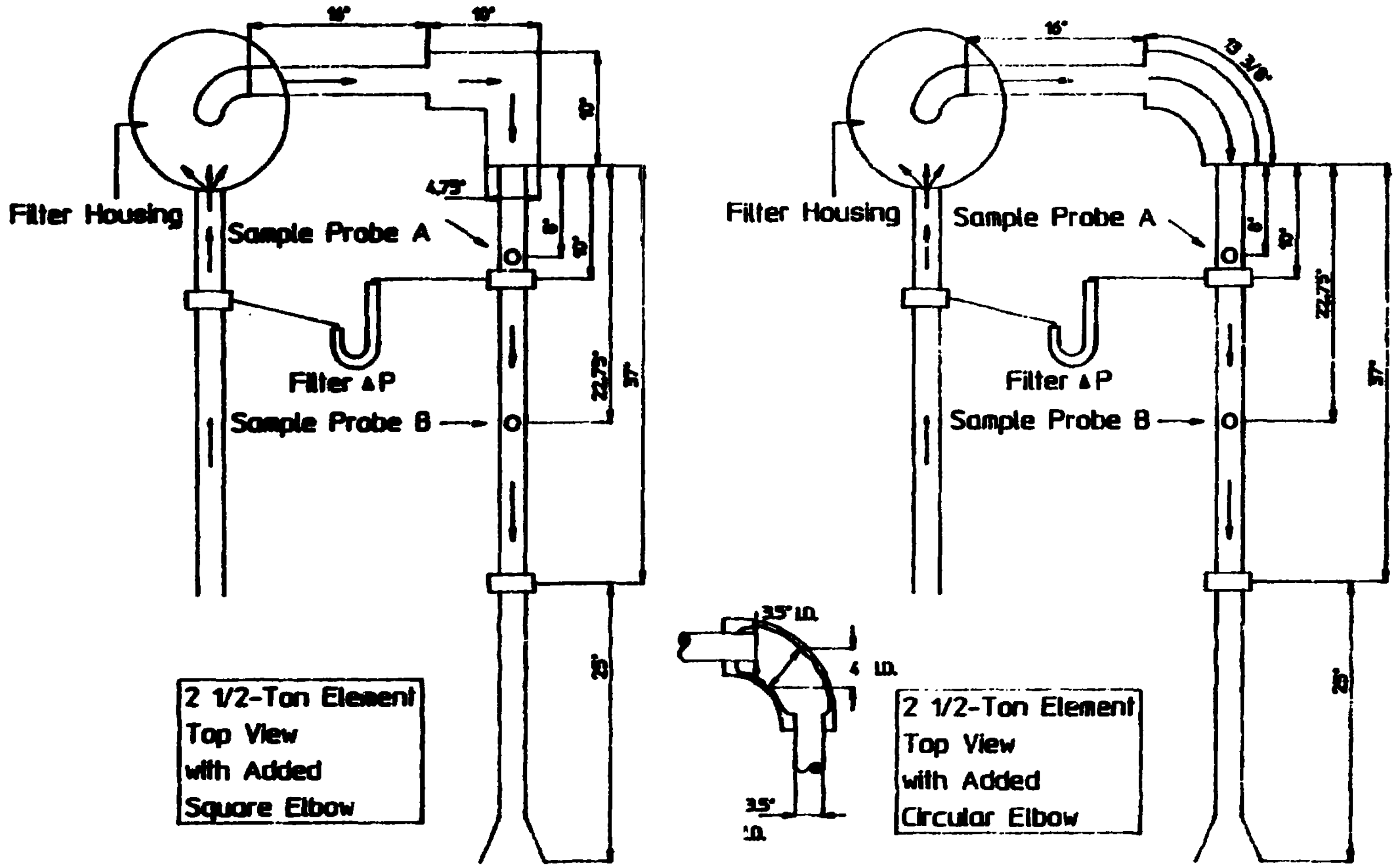


FIGURE 5-38. DUCT CONFIGURATIONS USED DURING THE TESTING OF SOME 2½-TON TRUCK FILTERS TO INVESTIGATE THE IMPACT OF DUCT CONFIGURATION ON SENSOR PLACEMENT AND RESPONSE

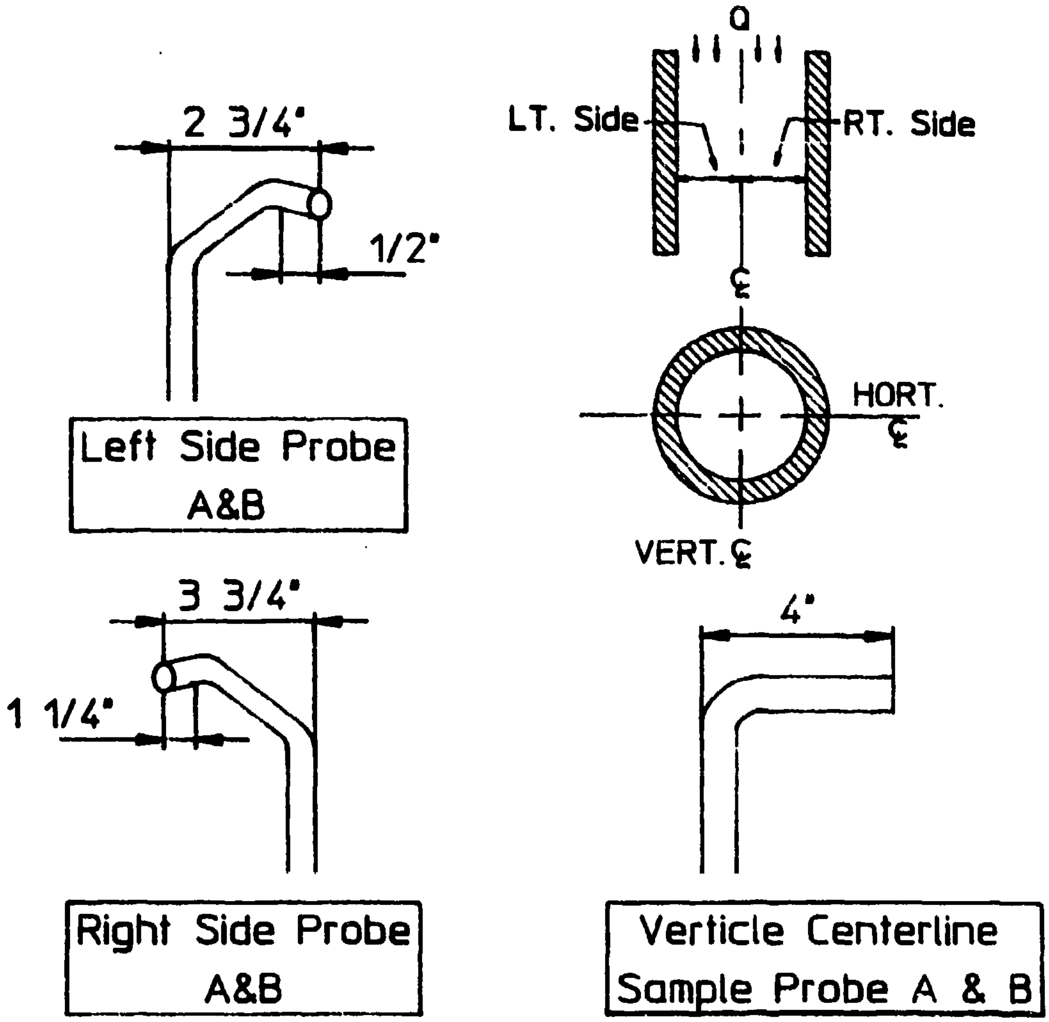


FIGURE 5-39. PROBE DISPLACEMENTS USED IN CONJUNCTION WITH FIGURE 5-38 DUCT CONFIGURATIONS

dimensional relative error sample parameter which gives a local relative particle density to the total (average) particle density inside the duct. This parameter is equal to 1 when a sample value is equal to the exact value, and increases (for the cases considered) as the sampling error increases due to the presence of increasingly skewed particle distributions.

The simulation does not address particle size, per se, and it is likely that particles of major interest to this project would alter the results somewhat because they would deviate more than the particles that were considered. The air temperature used was also too high, but

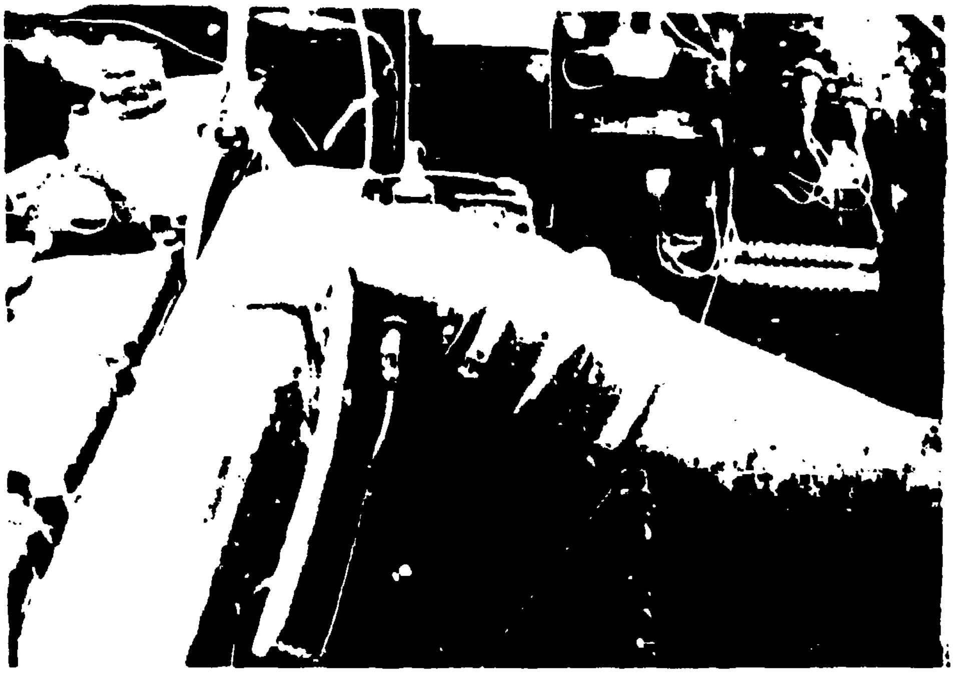
this should not change the results appreciably, as the flow would still be highly turbulent with Reynolds numbers much greater than 2000.

Dr. Bardina's results confirmed our concerns and findings about probe/sensor placement. His simulation showed that even for rather simple ducts, such as a straight duct with two opposite 90-degree bends, the actual particle distributions can skew significantly as a function of spacial location along and within the duct. For this reason, and because of the results of our other studies, it is strongly recommended that great care be given when considering interface locations for different vehicles, and for different air cleaner system geometries. This is imperative if the sample being analyzed for the "go"/"no-go" determination is to be reasonably representative of the actual in-duct environment. If it is not, the dust detector determination will be of little value.

5.5.3. Full-Scale Testing; 5-Ton Truck Mock-up. Following second-round testing, three units were subjected to full-scale laboratory test involving a mocked-up 5-ton truck air cleaner system. The major objective of this test was to investigate dust detector performance in conjunction with full-scale vehicle hardware, in a controlled environment which could be adjusted to simulate numerous field and air cleaner operating conditions.

In order to establish a test plan for full-scale laboratory testing, it was necessary to examine the air induction systems for the M809 and M939 series 5-ton trucks. As can be seen in Figures 5-40 and 5-41, differences exist in filter location, in the air induction ducting, and in other components of the air induction system for these two series of vehicles. In particular, there is a major difference in the connector assembly which is used to attach the air induction duct to the air intake manifold at the engine. For the M939 series, a port exists on top of the connector assembly for use with the PVC system. The problem is that this port is in the precise area where TACOM was hoping to install the dust detector sensor. Their choice of sensor location was based, in part, on the configuration of the specific M809 connector assembly which they had on hand, and on the assumption, as indicated in the technical manuals, that the same connector was used on both series of vehicles. This unit, provided earlier by TACOM for the full-scale test, did not have the PVC port located on top of the connector.

Concerning the connector, three alternatives seemed feasible: 1) use the M809 connector with the M939 ducting and filter assembly, and the M939 configuration; 2) use the M939 connector and M939 system with the PVC rerouted to another port on the connector, or 3) insert the test probes somewhere near the downstream end of the duct which attaches the connector assembly to the outlet of the air cleaner housing, as indicated in Figure 5-41. Options 1 or 2 would likely require the probe insertion area to be modified to accept the prototype sensors, at least during the laboratory test. A schematic of the 5-ton truck system is shown in Figure 5-42.



M809 SERIES

M939 SERIES

FIGURE 5-40. PHOTOGRAPHS OF M809 AND M939 SERIES 5-TON TRUCK AIR INDUCTION SYSTEMS

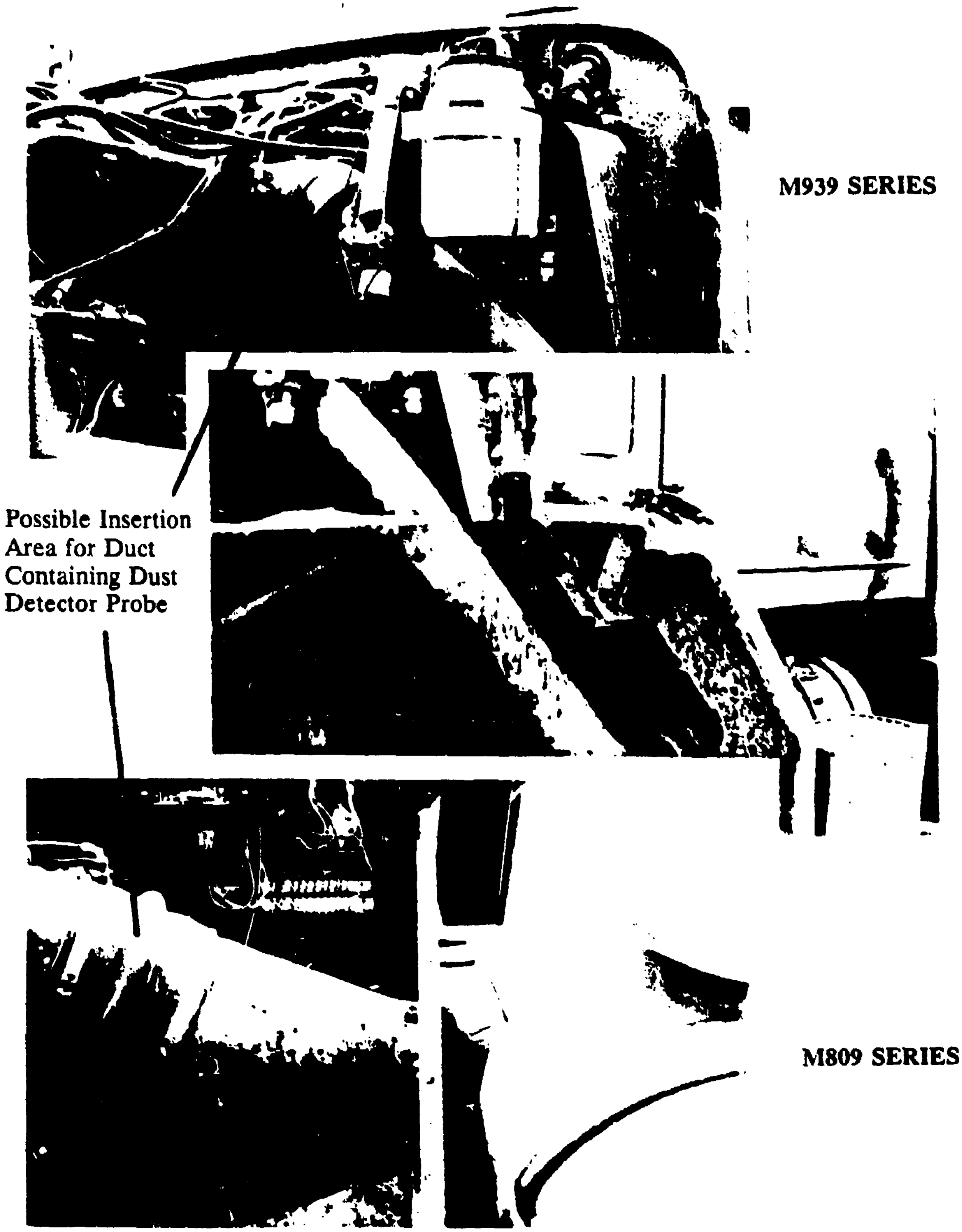


FIGURE 5-41. PHOTOGRAPHS OF M809 AND M939 SERIES 5-TON TRUCK AIR INDUCTION SYSTEMS

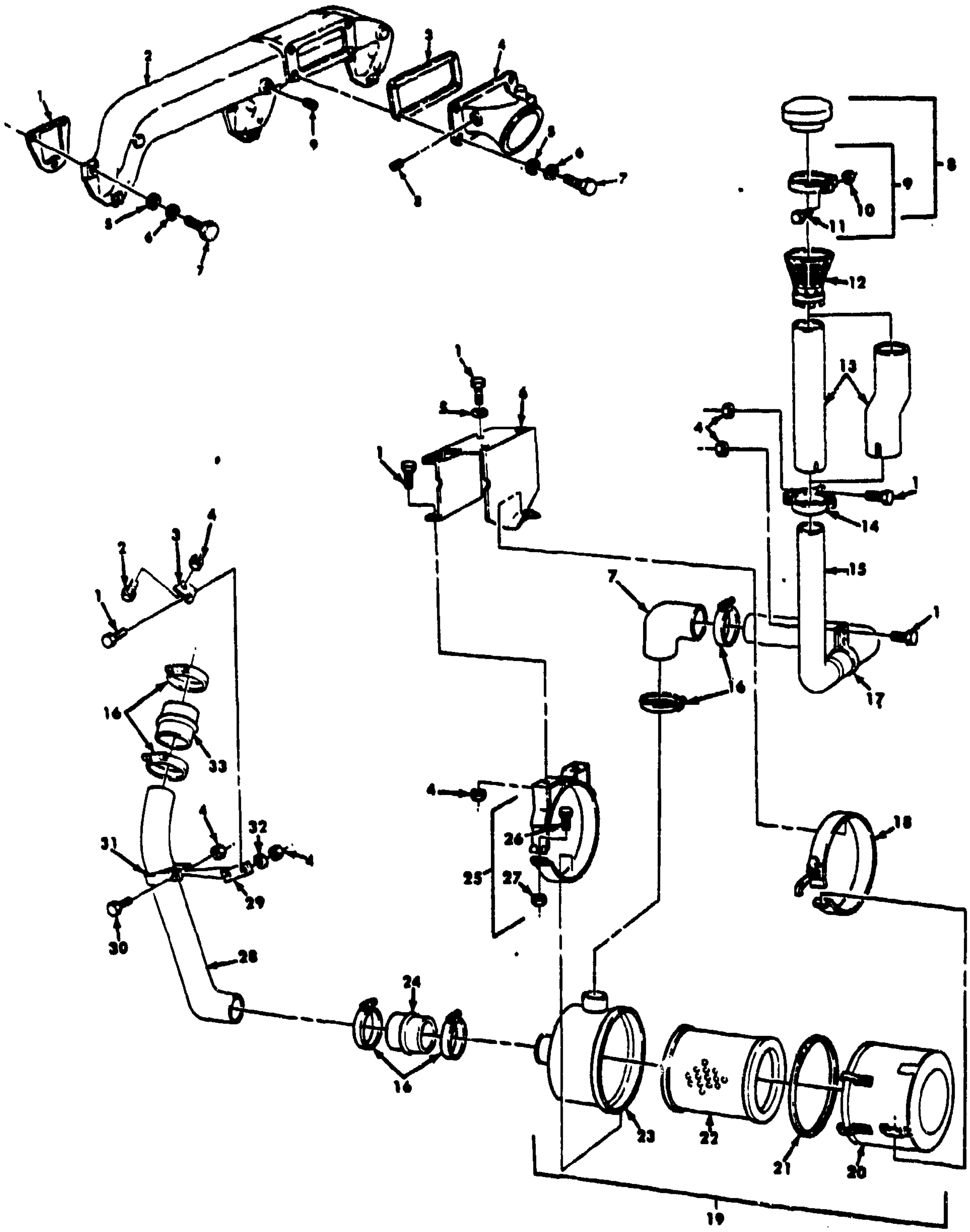


FIGURE 5-42. SCHEMATIC OF 5-TON TRUCK M939 SERIES AIR INDUCTION SYSTEM WITH M809 SERIES AIR INTAKE MANIFOLD (FROM TM 9-2320-272-34P-1; PAGES 82 AND 126, RESPECTIVELY)

The test arrangement selected for the full-scale 5-ton truck simulation is shown schematically in Figure 5-43 and pictorially in Figure 5-44. This system is basically the M939 configuration with the previously-mentioned M809 connector assembly modified to accept the HIAC/ROYCO dust detector, and with the manifold modified to accept the probes for the MET-ONE and ATCOR dust detectors, and the primary probe for the HIAC laboratory standard. Details of the detector and probe locations are given later. A standard inlet piezometer tube was used to direct the air flow and dust stream into the air filter inlet and to provide a means for measuring the pressure drop across the filter during testing. From the air cleaner inlet to the air intake manifold exit, the system represented a true mock-up of the M939 series 5-ton truck air induction system (with exception of the M809 connector). The air cleaner assembly and the outlet duct were positioned in their normal on-vehicle orientation. The engine air intake manifold, also positioned as on the vehicle, was connected to a duct leading to the absolute filter assembly so that all dust exiting the system could be accounted for. Prior to testing, the air flow characteristics of the system as a function of air flow rate were determined and the data are shown in Figure 5-45.

The reason for using actual vehicle hardware was to reproduce, very nearly, the flow state experienced by the system during operation, so as to expose each dust detector to conditions likely to be experienced during in-service operation. In this manner, each dust detector, depending on its specific position and orientation, would experience the effluent dust stream in much the same way as it would during service (with respect to this particular vehicle). The location of each dust detector is shown in Figure 5-46 and in more detail in Figure 5-47.

As can be seen, the HIAC/ROYCO unit was mounted on the manifold inlet adaptor so as to "look" across the flow stream in the main duct prior to the stream's diversion through the manifold entrance. With a focal length of approximately 3/4 of an inch to its (3mm x 0.1mm) sensing zone and with the unit centered laterally atop the adaptor section, the beam measured particles traveling near the geometric center of the adaptor's cross-section, which was somewhat compressed due to the near field flow obstruction caused by the interior edge of the adaptor's aspirator section located adjacent to the mounting area (Figure 5-47). Inlets to the ATCOR and MET-ONE test units and to the HIAC laboratory system were clustered just downstream of the HIAC/ROYCO sampling plane, in line with the expected stream flow at that point (Reference Figure 5-47). Probe inlets were sized to provide isokinetic sampling based on the air cleaner's rated (test) air flow and each unit's sampling flow rate.

5.5.4. Test Results. The data obtained during full-scale laboratory testing are presented and discussed below. From these data, and from consideration of the overall performance and functional requirements of the dust detector, it can be concluded that the HIAC/

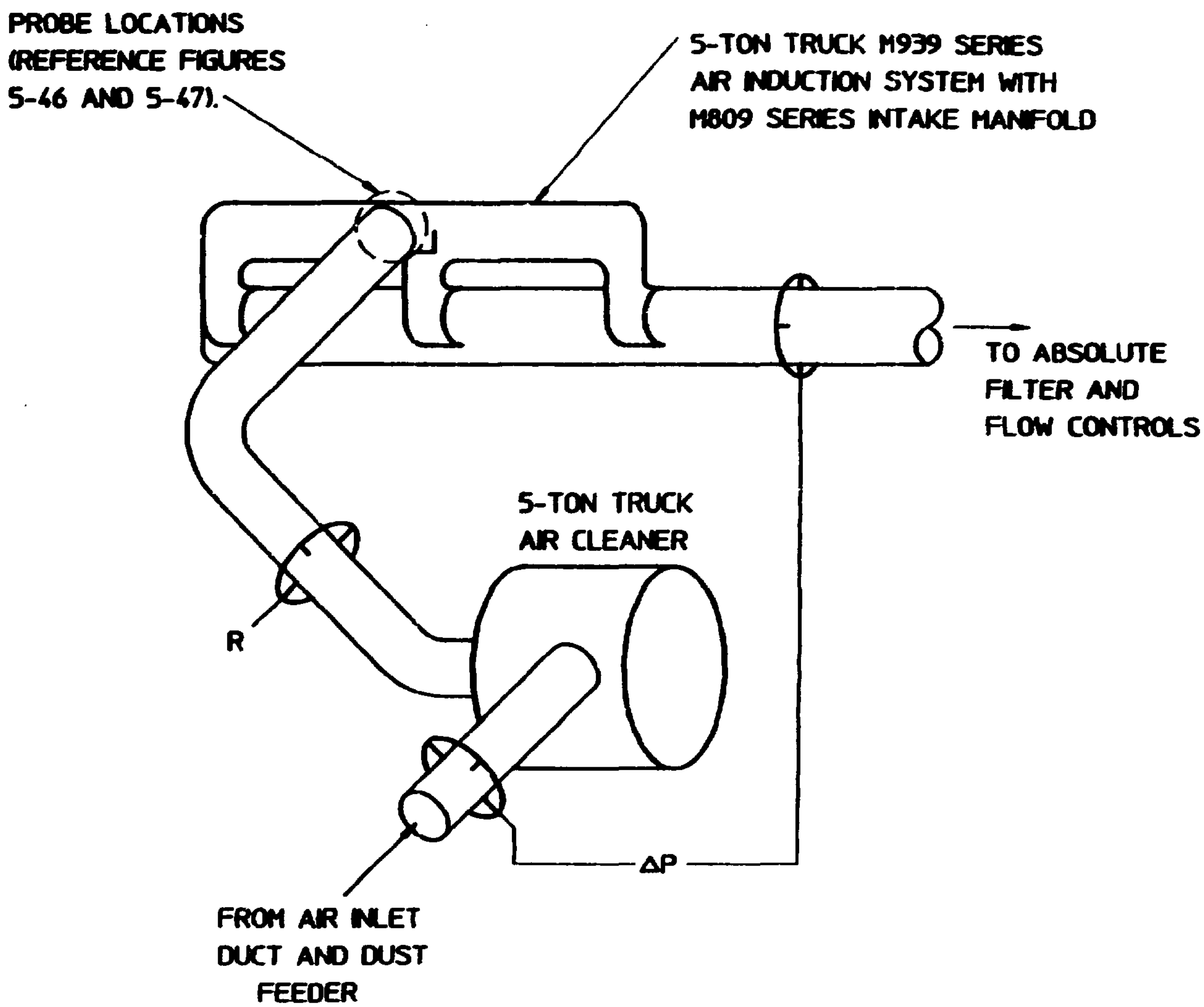


FIGURE 5-43. LABORATORY TEST ARRANGEMENT, FULL-SCALE 5-TON TRUCK MOCK-UP, SCHEMATIC

FIGURE 5-44. LABORATORY TEST ARRANGEMENT, FULL-SCALE 5-TON TRUCK MOCK-UP

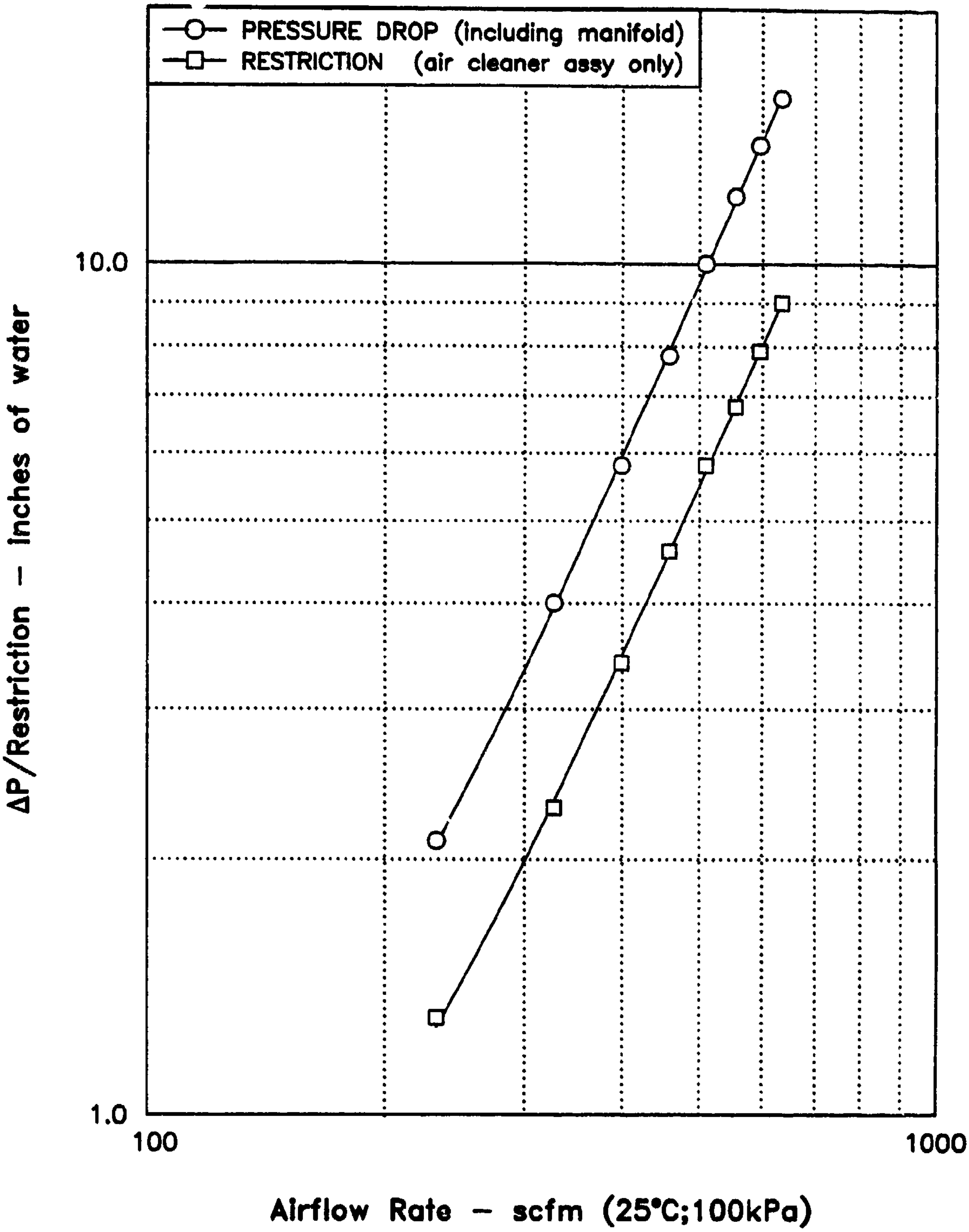
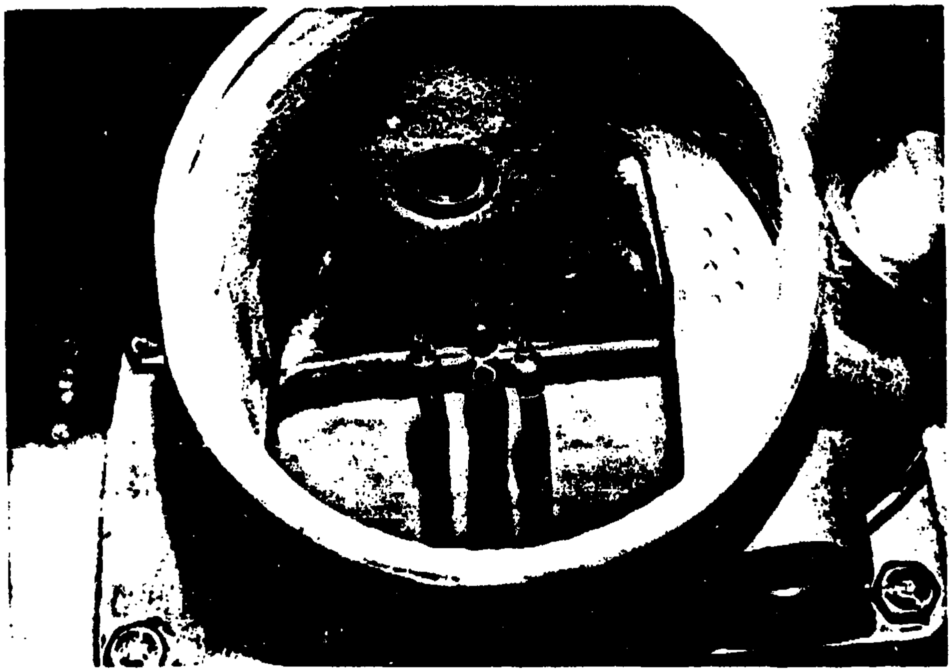


FIGURE 5-45. PRESSURE DROP AND RESTRICTION AS A FUNCTION OF AIR FLOW FOR 5-TON TRUCK MOCK-UP PRIOR TO FULL-SCALE LABORATORY TESTING (11604545 ELEMENT)



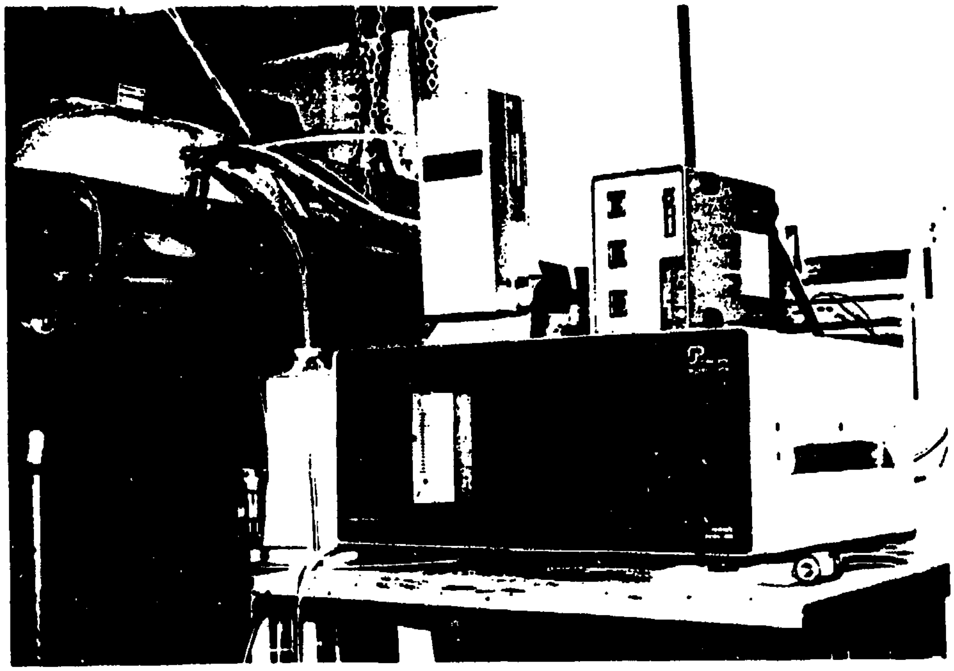


FIGURE 5-46. HIAC/ROYCO DETECTOR AND ATCOR, MET-ONE, AND HIAC PROBES DURING FULL-SCALE 5-TON TRUCK LABORATORY TEST (SEE FIGURE 5-47)

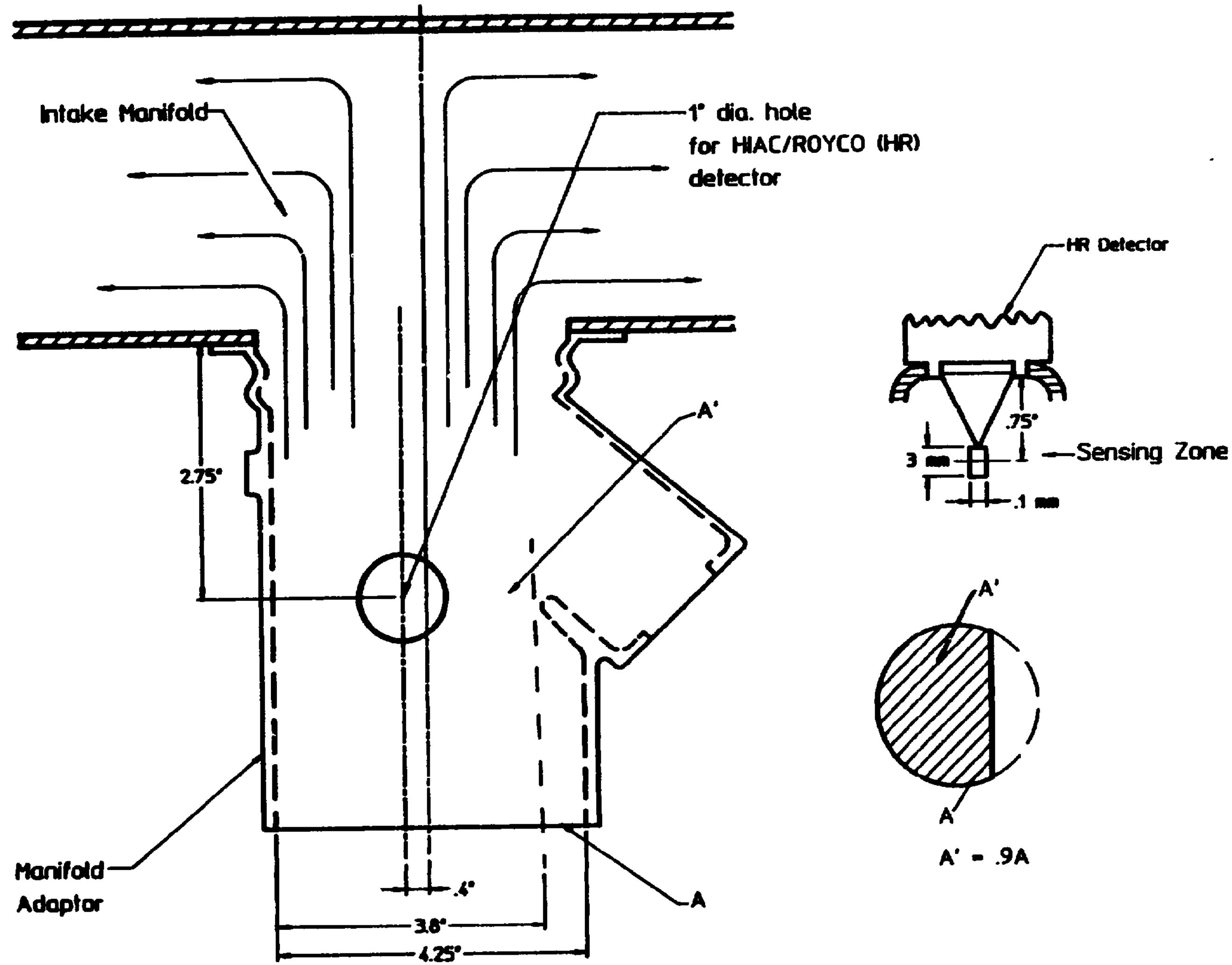


FIGURE 5-47. DUST DETECTOR LOCATIONS, FULL-SCALE TEST ON 5-TON TRUCK MOCK-UP

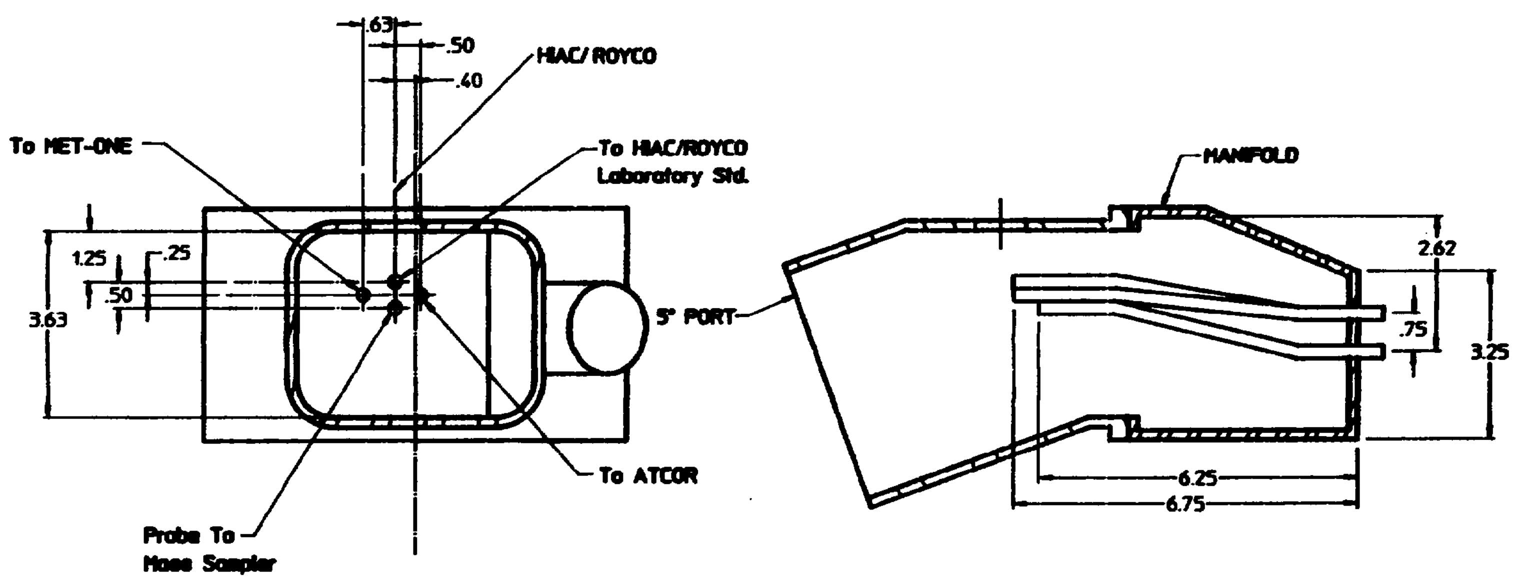


FIGURE 5-47. DUST DETECTOR LOCATIONS, FULL-SCALE TEST ON 5-TON TRUCK MOCK-UP (CONTINUED)

ROYCO technology, with its approach to particle sizing and concentration, is the unit of choice among the dust detectors evaluated.

Although in need of refinement and some further development, this unit, because it measures particle size and concentration with a single sensor, in-situ, (even as a preliminary prototype), showed significant promise and ability to function as a "go"/"no-go" particle discriminator. For this reason, it is recommended that the HIAC/ROYCO concept be pursued, with rapid prototype development, leading to a full-scale demonstration unit, being a major priority.

The other units tested, which measured particle size, but which ignored relating the particle size distribution to the concentration level in the duct, did not directly address the triggering criteria, and therefore will not fully function as appropriate dust warning systems. This is due, in part, because they do not provide a true measure or good indication of the in-duct environment, and because they are much more susceptible to particle sizing errors due to the non-isokinetic sampling conditions caused by their fixed sampling flow rates. Even if the sampling errors were tolerable, these units (because they operate at, and reference, a constant flow) will be much more vehicle-specific with respect to relating sampler data to some meaningful representation of the instantaneous in-duct environment. This is not to say that the ATCOR and MET-ONE technologies could not be modified to better infer or measure (in-duct) concentration levels. Rather, it says that the HIAC/ROYCO unit has already addressed this issue and arrived at a plausible solution to the problem. As such, the HIAC/ROYCO concept and hardware provide an advantage in terms of being less vehicle-specific and closer to being a usable system. In addition, the HIAC/ROYCO development team has a good understanding of the dust detector's requirements and its essential triggering and other operational features. This is a major reason why HIAC/ROYCO, from the outset, pursued a concept that addresses both particle sizing and particle concentration in the duct, which is, in fact, the basis for the triggering criteria. Furthermore, the HIAC/ROYCO technology appears hardenable to withstand rugged military environments, and adaptable to allow installation on a variety of vehicles. While the unit itself is not inserted in the duct, but rather is attached to the duct and interfaces through a clear window, it does, in fact, measure in-situ by creating a focal point that is located within the duct.

The test schedule is summarized in Table 13. At the start of testing, the air cleaner was exposed to AC Fine dust at a concentration of 0.005 g/ft^3 air for a period of 30 minutes. HIAC samples were taken periodically during this time frame to characterize the particle history of the (initial) effluent flow, and the dust detectors were monitored for their response. This part of the test was conducted at steady (rated) flow and very closely represented the initial efficiency tests typically performed on military and commercial filter elements. The low initial dust concentration provides a measure of filter performance in

TABLE 13. SUMMARY OF FULL-SCALE 5-TON TRUCK LABORATORY TEST

SEGMENT	HIAC RUN				
840	1 - 11	At start of test; initial dust feed @upstream concentration of 0.005 g/ft^3 air (AC Fine dust) 30 sec. sample/0.1 cfm HIAC			
	1 - 6				
	7 - 11	10 sec. sample/0.1 cfm			
813	1 - 20	10 sec./0.1 cfm AC Fine @.005 g/ft^3 air upstream			
814	1 - 8	AC Coarse dust @0.025 g/ft^3 air, to variable flow schedule:			

	HIAC	FLOW SCHEDULE		
1-2	10 sec/0.1 cfm	0-10 min.	100%	550 cfm
3-8	60 sec/0.1 cfm	10-20	60	330
		20-30	20	110
	low HIAC flow	30-40	80	440
	@ end of 6-8,	40-50	60	330
	est 80% - 60%	50-60 min	40	220

estimated dust
to be fed ~495 g/hr

Ran 1 hour (1 complete cycle)

SEGMENT	HIAC RUN		
815	1 - 5	140.6 g/10 min.	HIAC: 30 sec/0.1 cfm 10-0.041 dia. holes in pleat edges (B) 137.5 g/10 min/AC Coarse 550 cfm (steady flow)
	6 - 10	136.0 g/10 min.	increased holes to 0.125 dia.
816	1 - 5	132.5 g/10 min.	added 10 more 0.125 dia. holes
	6 - 10	134.6 g/10 min.	added 10 more 0.125 dia. holes
	11 - 15	131.8 g/10 min.	added 10 more 0.125 dia. holes

TABLE 13. SUMMARY OF FULL-SCALE 5-TON TRUCK LABORATORY TEST (Continued)

SEGMENT	HIAC RUN		
817	1 - 6	175.3 g/10 min.	portion of seal removed (3/4")
	7 - 12	137 g/10 min.	30 sec./0.1 cfm HIAC
818	1 - 12	275 g/20 min.	30 sec./0.1 cfm HIAC
819	1 - 13	274.1 g/20 min.	30 sec./0.1 cfm HIAC
	End of Test		

the earliest stages of operation prior to any appreciable dust loading. As noted, this is a critical time for the dust detectors because of the large numbers of particles which typically penetrate even under normal operation.

Following the initial efficiency test, the air cleaner was exposed to AC Coarse dust at a concentration of 0.028 g/ft^3 air, following a variable flow schedule typically used in military air filter testing (for instance, for the Bradley). During this segment, one complete cycle was accomplished with 498 grams of dust being fed. AC Coarse dust was used because this is usually the contaminant of choice when testing two-stage air cleaners such as that used on the 5-ton truck.

Next, the air cleaner assembly was subjected to Coarse dust (0.028 g/ft^3 air) in a series of steady-state (550 scfm) tests, some of which included induced faults. After obtaining a baseline at steady flow, under normal operation, ten 0.041-inch diameter holes were drilled in the pleat edges to simulate filter leakage. The size of these holes was increased to 0.025 inch diameter and additional 10-hold groups were sequentially added to increase filter deterioration. Finally, a 3/4-inch portion of the seal was removed, further decreasing filter performance, while increasing the amount of dust sent to the detectors.

In all, approximately 2183 grams of dust were fed to the air cleaner during full-scale 5-ton truck testing. As shown in Figure 5-48, the air cleaner experienced a pressure drop increase of 2.7 inches of water, from 6.5 to 9.2, even with induced fault operation. In addition to their response to dust exposure, detector response was monitored as a function of airflow fluctuations without dust ingestion. It should be noted, however, that even when no new dust was not being fed to the air cleaner, dust already in the "system" could be re-entrained during air cycling later in the test, particularly after the filter was modified to simulate induced fault operation.

5.4.4.1. Data Analysis; HIAC/ROYCO Detector. Data for the HIAC/ROYCO detector, during the full-scale 5-ton truck laboratory test, can best be analyzed on a scatter plot which shows sensor response in terms of being "on", "off" or in a "threshold" condition (toggling on and off) with respect to specific test conditions and to the dust detector triggering criteria. Results for eighty-nine different challenge conditions are shown in Figure 5-49. As can be seen, a fairly broad range of conditions induced threshold-mode operation (on/off toggling), probably due to the short integration time employed. Improved performance, in this regard, could likely be obtained by employing longer signal averaging [the HIAC/ROYCO prototype was preset to provide one second averaging (integration)]. A useful feature of the HIAC/ROYCO design is that a long integration time does not prevent rapid response to extreme particle concentrations, but does allow an extended response time for concentrations in the near-threshold area so that false triggering can be minimized. The test data further show that the sensor was always off for

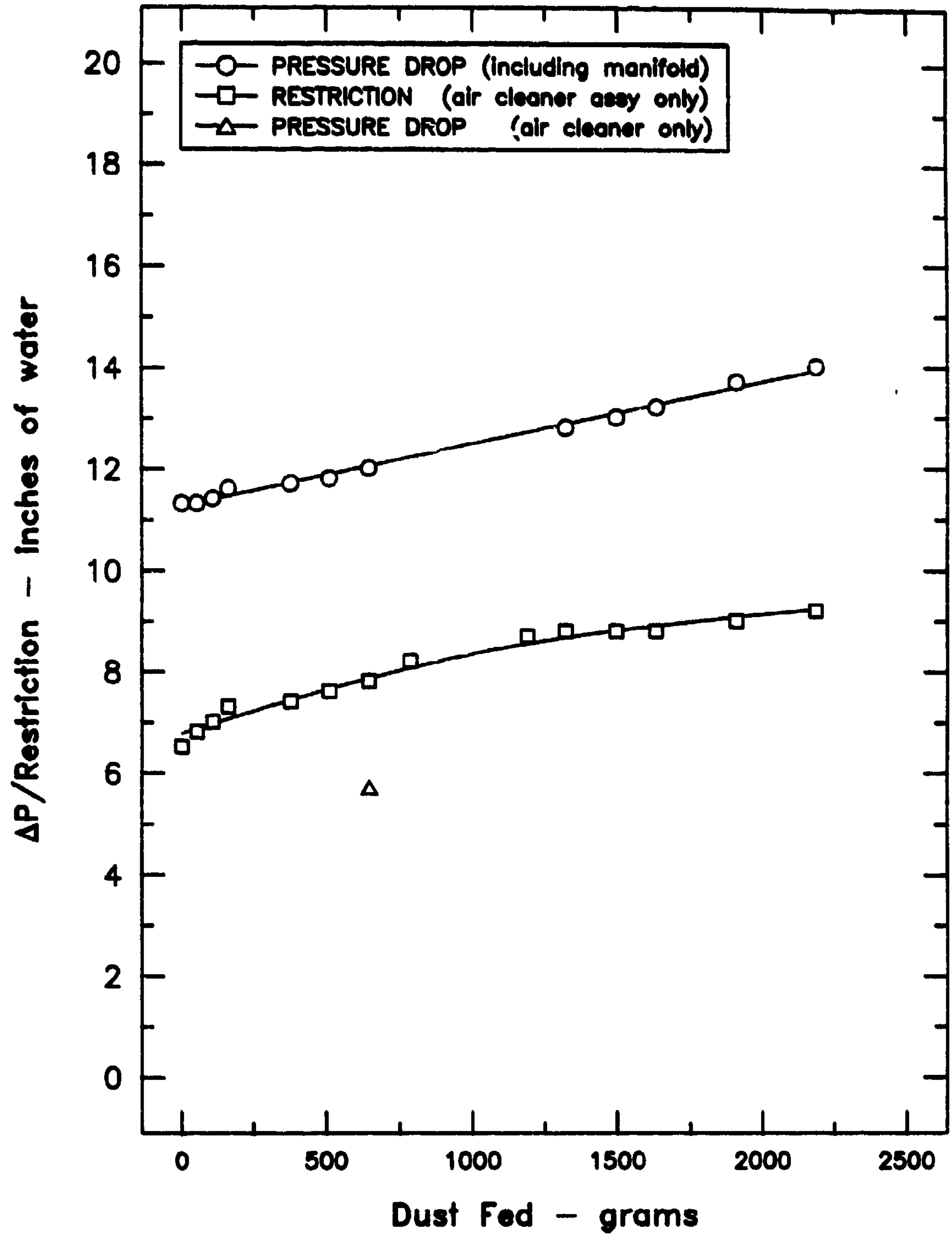


FIGURE 5-48. FILTER DUST LOADING HISTORY (ΔP VS DUST FED) DURING FULL-SCALE 5-TON TRUCK LABORATORY TEST

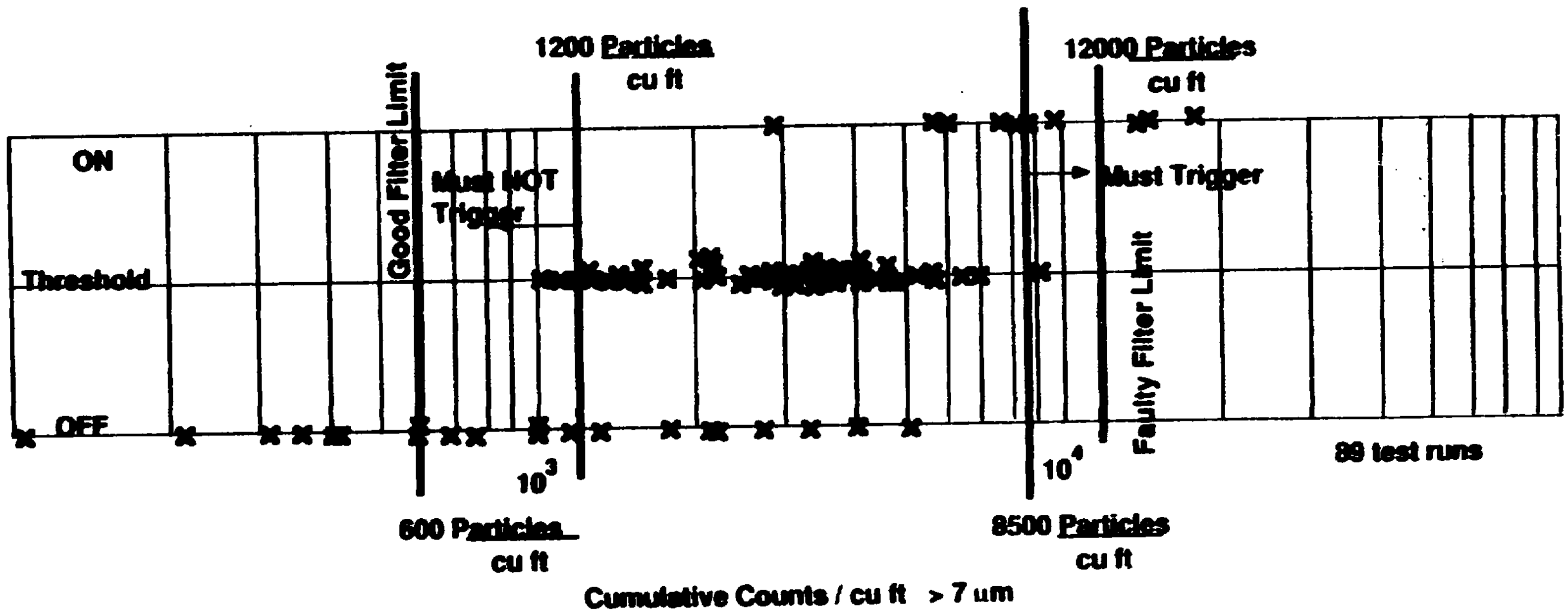


FIGURE 5-49. SCATTER PLOT OF HIAC/ROYCO RESPONSE DURING FULL-SCALE 5-TON TRUCK LABORATORY TEST

"clean enough" conditions, and always on for "dirty enough" conditions. In fact, with few exceptions, all of the "must trigger" trials and all of the "must-not trigger" trials were correctly interpreted, with the exceptions lying barely outside of the specification limits.

5.4.4.2. Data Analysis; MET-ONE Detector. Responses for the MET-ONE instrument, which pulls a sample from the main duct for external sensing, are shown in Figures 5-50 and 5-51. Both second round bench testing and the results of the full-scale 5-ton laboratory test are shown. Like the HIAC/ROYCO analyses, these data are presented to show the "on," "off," and "threshold response" of the instrument, whose concentration threshold was periodically changed during testing to respond to three specific set points, namely 50, 100 and 250 thousand particles per cubic foot air. The data in Figure 5-50 show that the transition zone during bench testing was fairly well confined to the 3-4μm range, whereas the same zone during full-scale testing was confined to the 4-4½μm range for all concentration set point limits. Figure 5-51 was developed by looking at the HIAC particle counts in terms of concentration (number per cubic foot) for particle sizes (dp) greater than 3μm, 5μm, 7μm, and 9μm for sixty-four different test conditions encountered during both series of tests. When these data were plotted to show the cumulative concentration of particles (number of particles per cubic foot) having diameters greater than dp, and when the corresponding on-off responses for a particular concentration set point were examined, it was possible to determine the particle size range associated with each response. In addition, examining each curve at the 7μm point gave a direct indication of the concentration for particles exceeding 7μm.

It is important to note that the MET-ONE unit sampled continuously, at a constant 0.1 cfm flow rate, and that the samples were analyzed externally from the duct. It is also important to note that while the instrument was reportedly preset to respond to particles 7μm and above, it instead responded to particles in the 3-5μm range, independent of the concentration set point. The data do show, however, that for a given particle threshold, the instrument responded well to particle concentration level. One reason why the instrument may have responded in the wrong particle size range is that the original calibration was conducted on monodispersed latex spheres, whereas the laboratory evaluation was conducted using a polydispersed dust composed of non-spherical, non-ideal particles.

5.5.4.3. Data Analysis; ATCOR Detector. Data from the ATCOR unit were analyzed by comparing projections for cumulative concentration in the 5-7μm range with cumulative data obtained with the HIAC. This approach was necessary because, even though the ATCOR unit had been modified to examine higher particle size distributions, the ATCOR

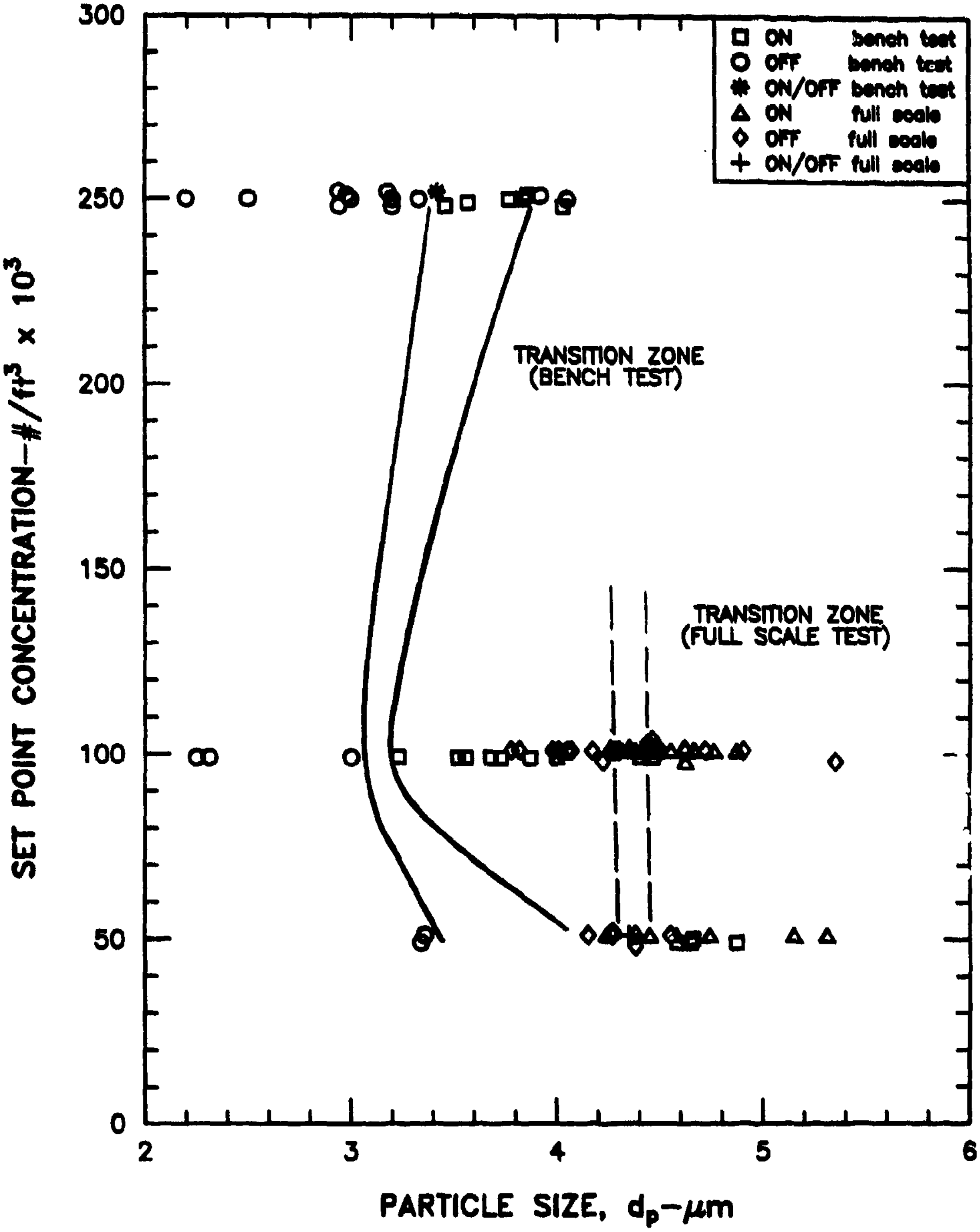


FIGURE 5-50. MET-ONE TEST RESULTS, 5-TON TRUCK FULL-SCALE TEST, RESPONSE AS A FUNCTION OF PARTICLE SIZE

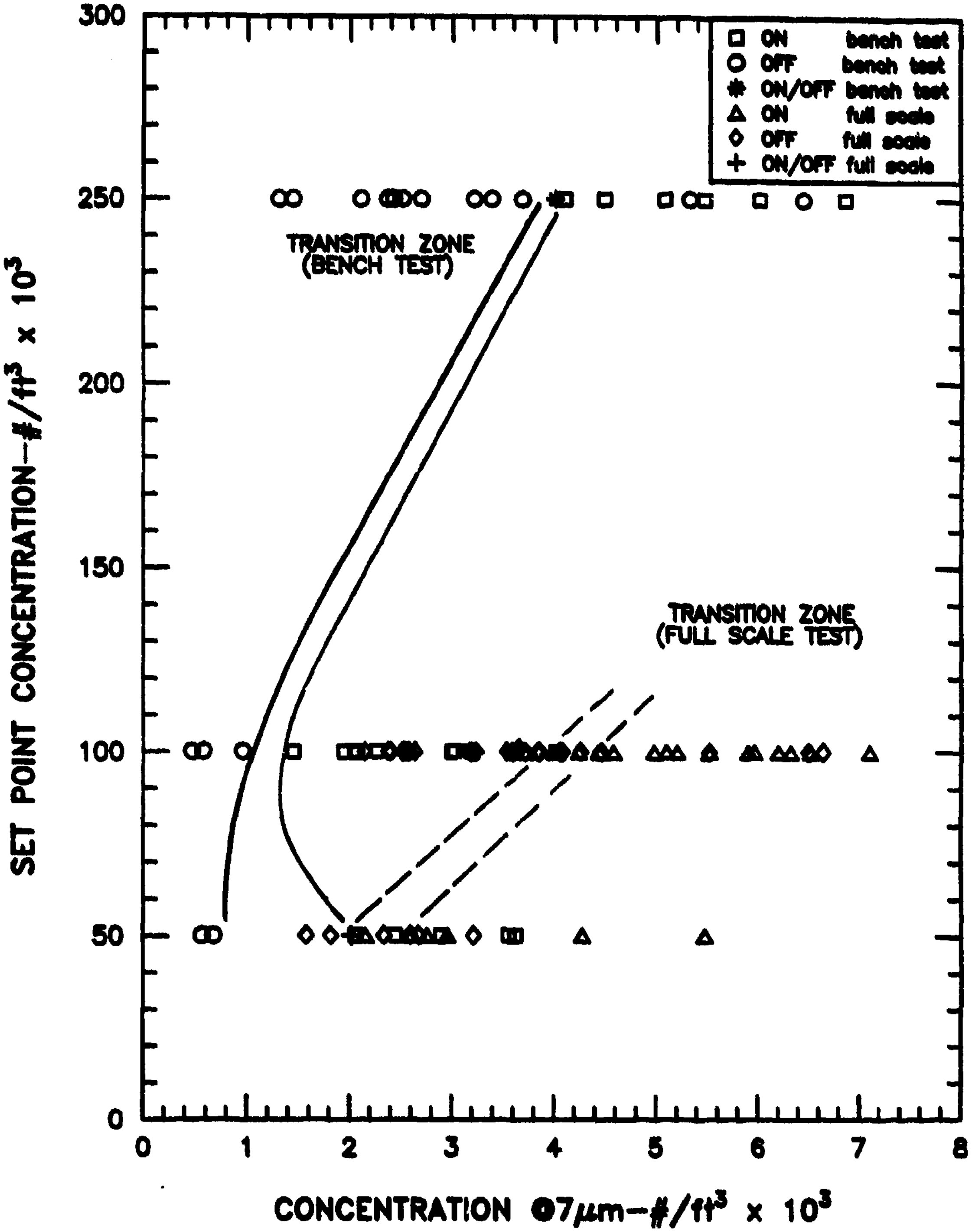


FIGURE 5-51. MET-ONE TEST RESULTS, 5-TON TRUCK FULL-SCALE TEST, PROJECTED CONCENTRATION AT 7μm

readout only provided data relative to the four original threshold settings, namely 0.5, 0.7, 1 and 5μm. During operation, particle size data are gathered for all channels simultaneously and can be assessed on either a cumulative or differential basis. In the cumulative mode, the information displayed is the total number of particles (or particles per cubic foot) of a size greater than or equal to the selected channel size. In the differential mode, the information displayed is the number of particles (or particles per cubic foot) of a size falling in the range between the selected channel and the next larger channel. Since the sampling rate to the sensor is fixed at 0.1 cubic feet per minute, the rate at which particles are counted can be converted to particles per cubic foot. The sampling time was set at one minute.

An example of the bench test data and data from full-scale laboratory testing are shown in Figures 5-52 and 5-53, respectively. As can be seen, reasonable correlation is shown in the area of interest by comparing like test runs. Examining the remaining test data in a similarmanner indicated that the internal modifications made to the ATCOR sensor after first round testing did improve sensitivity to particles in the 5 and 7μm range, which is the range of interest. It remains to be seen and demonstrated, however, how well the instrument will respond to triggering criteria which consider both particle size and particle concentration. Furthermore, it must be noted that the ATCOR unit is a constant volume sampler, and therefore does not relate measured concentration values to in-duct concentration values, as discussed earlier for the MET-ONE detector.

To be useful, the in-duct concentration issue must be addressed. Nevertheless, test results for the ATCOR detector indicate that the particle sensing technology for the modified laboratory unit will respond to particles in the area of interest and could form the basis of a usable dust detector.

5.5.5. Field Visits. During the project, field visits were made to four M60 installations to discuss M60 dust detector usage. The purpose was to obtain field/user input concerning the dust detector concept and its method of implementation and utilization. It was particularly important to address specific field concerns and gain additional information with respect to user expectations and requirements. For instance, we were aware that false triggering would create a nuisance which would ultimately undermine user confidence, and hence, the usefulness of the dust detector as a warning device. We also suspected that, in many cases, the vehicle operator is already required to monitor several gauges, so that adding another requirement must be carefully thought out and justified. Since the intent of the dust detector is to provide a warning based on "go"/"no-go" criteria to alert the operator of an impending problem, it should likely remain unobtrusive under normal

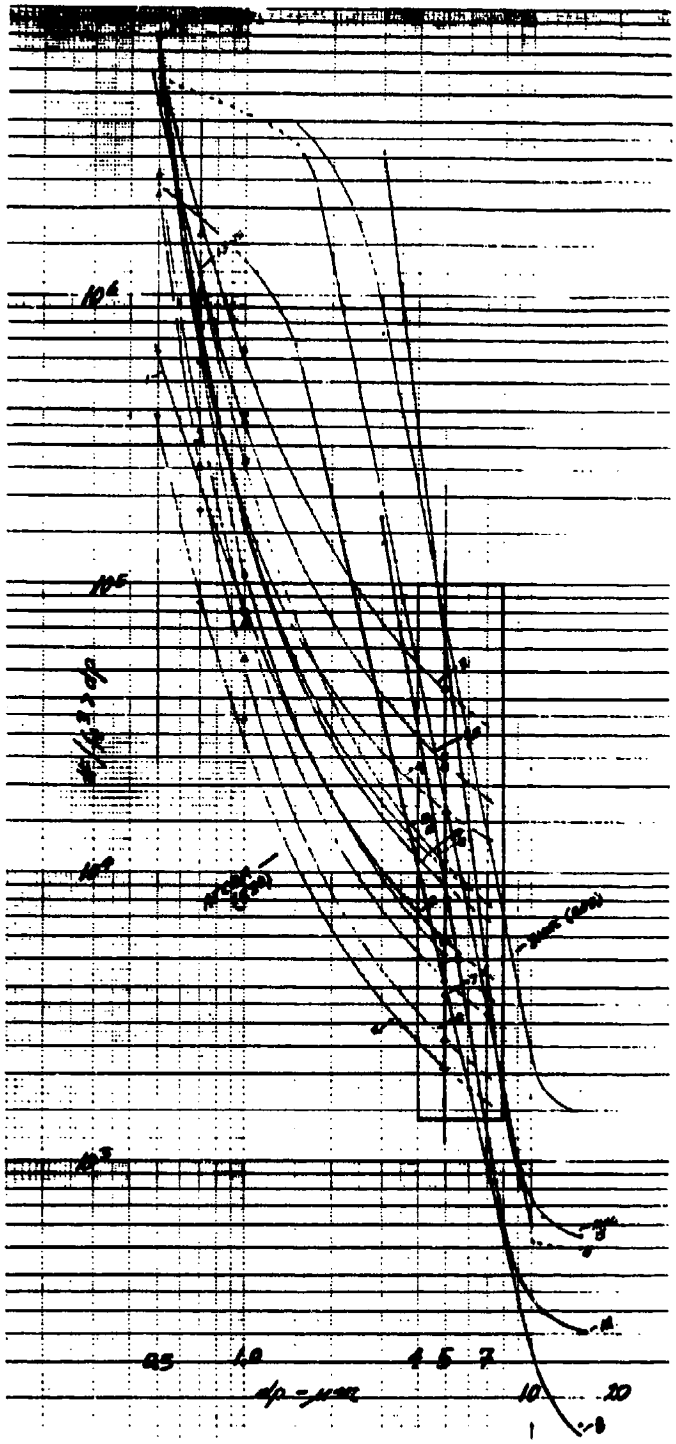


FIGURE 5-52. SAMPLE DATA FOR ATCOR UNIT DURING SECOND ROUND BENCH TESTING

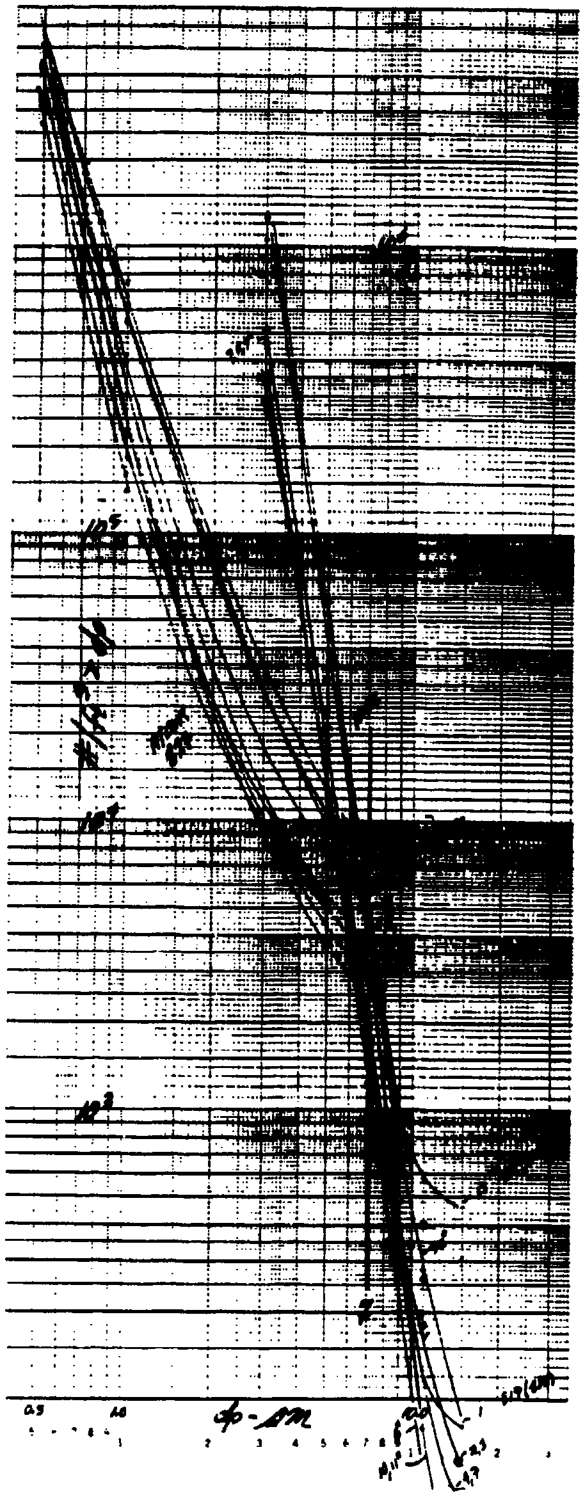


FIGURE 5-53. SAMPLE DATA FOR ATCOR UNIT DURING FULL-SCALE 5-TON TRUCK LABORATORY TESTING

operation while triggering an alarm only when the "no-go" criterion has been exceeded. It was therefore considered beneficial to meet with M60 operators to discuss their concerns and to obtain their input and suggestions, particularly with respect to questions regarding human factors, machine interfacing, system usability, and special requirements where operator and maintenance inputs were of concern.

Overall, it was felt that information gained on these visits would be very beneficial in helping the military obtain a worthwhile, useful maintenance tool that would not only enhance operational readiness and mission preparedness, but also reduce overall maintenance costs and downtime. Under TACOM guidance, it was decided that the field visits would target M60A3 units, since the M60A3 currently had a "dust detector (indicator)". As a result, trips were specifically made to Fort Carson, CO; Twenty-Nine Palms, CA (Marine Corps); Fort Erwin, CA; and to the Boise Army National Guard Unit in Boise, ID.

Results from these visits were essentially the same, namely, there was consensus that a reliable, real-time dust detector would be a welcomed item, which could help reduce or eliminate many problems and much of the damage caused by faulty air induction systems. Key points of discussion emphasized reliability, functionality, and real-time responsiveness.

During the Fort Carson visit, data from the Army Oil Analysis program for all vehicles at Fort Carson were reviewed. These data, covering a period from late 1987 to mid-1988, concerned potential air induction problems that were indicated by detection of high silica levels during engine lube-oil analysis. The list of these problems was quite long. A review of the data showed that many problems would likely have been detected by a real-time, properly placed dust detector. Furthermore, this would have allowed corrective action to be taken immediately, rather than allowing the vehicle to continue in-service with the problem uncorrected until the problem was indicated by the oil sample analyses. Discussions at the field level (M60 maintenance personnel and crews) were also supportive of a real-time dust detector. With respect to the current "dust detector" on the M60's, the following comments are noteworthy:

1. Crews pay attention to the warning light when it works; however, by this time, it is usually too late as far as preventing dust ingestion is concerned.

2. The warning light often false triggers because of electrical shorts caused by pinched wires (this is due to the wire routing scheme which invites cover interference in the engine compartment).

3. Overall circuit reliability is low; that is, the warning light does not always trigger when it should or, conversely, it triggers when it should not.

There was also some concern (at IMMO) that the present warning system is ignored, or at least, not always used properly. This points out the need to tamper-proof the dust detector so it cannot be unplugged or easily rendered inoperative. To discourage crews from ignoring the warning, a means of logging (automatically) the warning event in the maintenance record may be appropriate.

Results from the visits to the other three installations were in line with those from the Fort Carson visit; namely, there was consensus that a reliable, real-time dust detector would be a good item. In particular, in most cases it would allow air induction problems to be identified early enough so that corrective action could be taken before significant engine damage is encountered.

The real-time dust detectors currently under consideration will do away with many of the problems associated with the "dust detector" presently used on the M60A3's. For instance, consider one of the major weaknesses associated with the current system, as illustrated by its general method of operation. Currently, when the warning light comes on, the vehicle is stopped and the cause of the problem is sought. Procedurally, this means inspecting and cleaning the dust detector sensor and the air induction system, and then resetting the detector. If the warning light goes out, vehicle operation is continued; however, there is often no certainty as to whether the true problem has been resolved because, even in the event of a failure, the new tape takes time to load up and re-trigger the light. A real-time dust detector that only triggers in response to actual dust concentration levels in the inlet duct (to the engine) would remove this uncertainty.

During vehicle operation, the current M60 dust detector pulls a fraction of the induction air through a filter strip mounted in the turbocharger compressor housing. When the filter strip collects sufficient dust to reach a preset restriction, a pressure switch actuates a warning light in the driver's compartment. Two units are employed: one on each engine bank compressor. Obviously, this system operates with a large time constant. In addition, it is susceptible to dust loading by small particles over extended periods of time, and this can lead to false triggering, as noted earlier when discussing insertion type probes.

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APPENDIX A

DISCUSSION OF EXTREL PROBE

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EXTREL

EXTREL's contention that the fouling of their probe was caused predominately by large particles, because AC Coarse Test Dust was used, is incorrect and inconsistent with their discussion of the SwRI test set-up. During testing, both AC Coarse and AC Fine dust were used. However, in all cases, the particle size distribution and concentration levels were purposely altered to obtain the desired aerosol in the test area. This was accomplished by adjusting the dust feeding mechanism and the precleaner scavenge flow, and by using foam and paper filter elements as needed. The purpose was to tailor the aerosols so that specific distributions presented to the sensor would simulate various stages of normal and abnormal filter operation, as measured during full-scale testing of 2½ and 5-ton truck and M2/M3 air filter systems.

EXTREL is also incorrect in their thinking that longer-term, full-scale testing using an actual vehicle, would provide a different (more favorable) result for their detector. During such a test, it is very likely their probe would become coated with small particles and become desensitized in the same manner as during the laboratory testing. The reason for this is that a standard military filter elements passes a very large number of small ($\leq 5\mu m$) particles, for a considerable period of time. As a result, even though the collection efficiency of the EXTREL sensor seems relatively low for these particles, (less than 25 percent, reference Figure A-1), the fact that such a large number of particles will be present in the air stream makes it highly likely that a significant number of particles will impact the sensor during the dust loading process. This will undoubtedly lower the probe's sensitivity, making it unfit for subsequent use as a particle detector. In fact, sensitivity impairment during exposure to normal downstream dust levels would preclude detection of a filter problem should one occur later in the loading cycle.

The curve presented in Appendix B of EXTREL's letter, showing the theoretical collection efficiency for particles impacting a ¼-inch diameter cylinder, is incorrect and inappropriately applied. The reason the curve is incorrect is two-fold. First, the equation used for Stokes Number for a cylinder should have been $(V_f/D)\tau$ rather than $(V_f/R)\tau$. Since EXTREL used R instead of D (1/8" instead of1/4"), their curve should have shown the impaction efficiency of the pre-impactor, which did in fact have a 1/8-inch diameter. Yet, even for this case, the curve in Appendix B is not correct. As it turns out, the EXTREL curve much more closely represents the impaction efficiency of the 1/32-inch diameter sensor, as shown

in the insert in Figure A-1. The correct curve for the 1/8 inch pre-impactor is also shown. Both curves were developed from the same equation used by EXTREL, ref. Figure A-2.

The configuration of the EXTREL probe is shown in Figure A-3. For this configuration, the likelihood that particles will impact the sensor can be calculated by combining the collection efficiency of the sensor with the inefficiency of the pre-impactor, as a function of particle size, for collection by impaction only. The result is shown in Figure A-4. Two things are noteworthy: a) the collection potential for small particles just below the threshold is quite high, although it drops rapidly as particle size decreases. This means that a large number of small particles (sub 7μm) will likely impact the probe because there will be a large number of these particles in the flow stream; b) the collection efficiency for the particles of interest ($\geq$7μm) is relatively low. This means that over half of the particles of interest will probably not be detected by the sensor.

CONFIGURATION OF EXTREL PROBE

The curve in Figure A-4 suggests that a potential solution to the problems of small particle fouling and large particle pre-impaction (for the EXTREL probe) could be to design the sensor element into some type of impactor plate situated behind an impaction nozzle or jet, as shown in Figure A-5. This arrangement could likely be designed to give a rather steep cut-off curve, as a function of aerodynamic particle size, in the airflow range of interest. As shown in Figure A-6, this could allow much better discrimination in the threshold area. Such a sensor would require significant development, but could solve the above-mentioned problems, which, at present represent major shortcomings for the EXTREL probe. Further analysis is required to better characterize the potential of this approach and to consider its appropriateness for vehicle applications.

Another approach would be to direct a portion of the particle stream through an inertial separator having a design cut size near the 7μm threshold unit. The underflow stream (particles <7μm) would be direct away from the sensor (to reduce rapid fouling), while the overflow stream ($\geq$7μm) would be directed toward the sensing filament. This scheme could greatly increase the element's useful life by reducing, but not eliminating, fouling.

Since the characterization of probe performance, as far as particle size information was concerned, depended heavily on the HIAC readings, an analysis of the sampling procedures and their impact on particle counting and sizing is in order. It has already been pointed

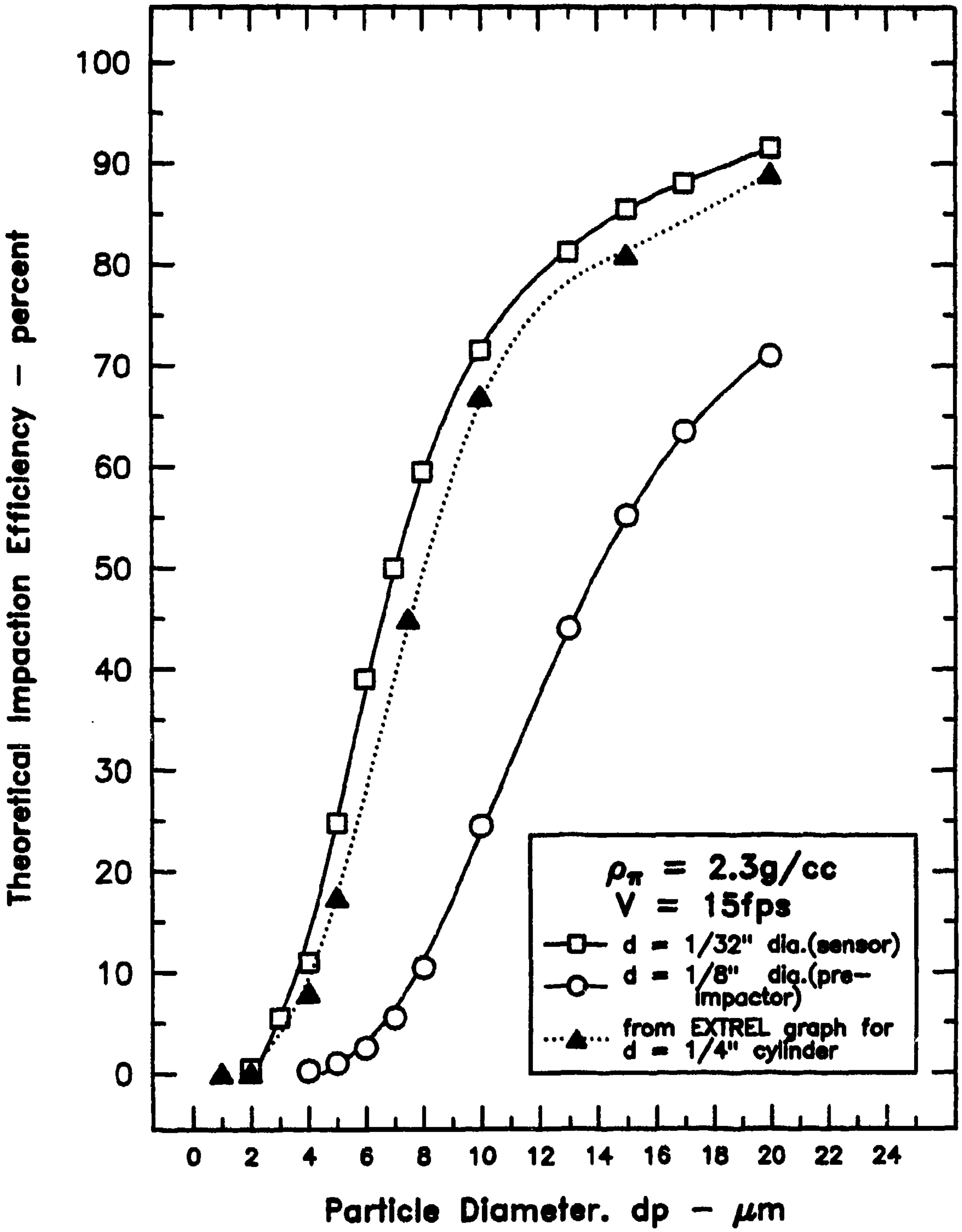

FIGURE A-1. THEORETICAL IMPACTION EFFICIENCY AS A FUNCTION OF PARTICLE SIZE, EXTREL SENSOR AND IMPACTOR

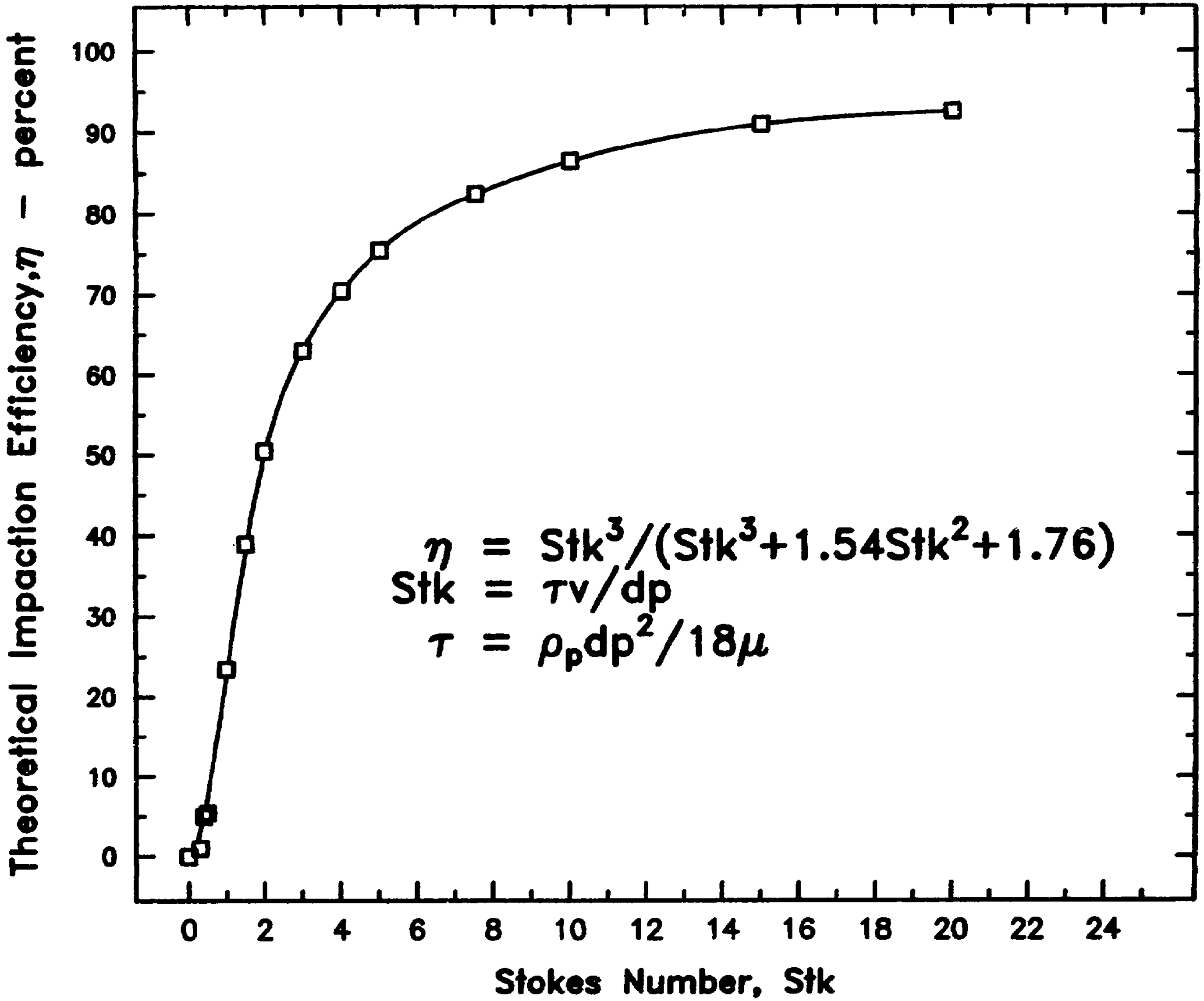

FIGURE A-2. IMPACTION EFFICIENCY ON A CYLINDER AS A FUNCTION OF STOKES NUMBER

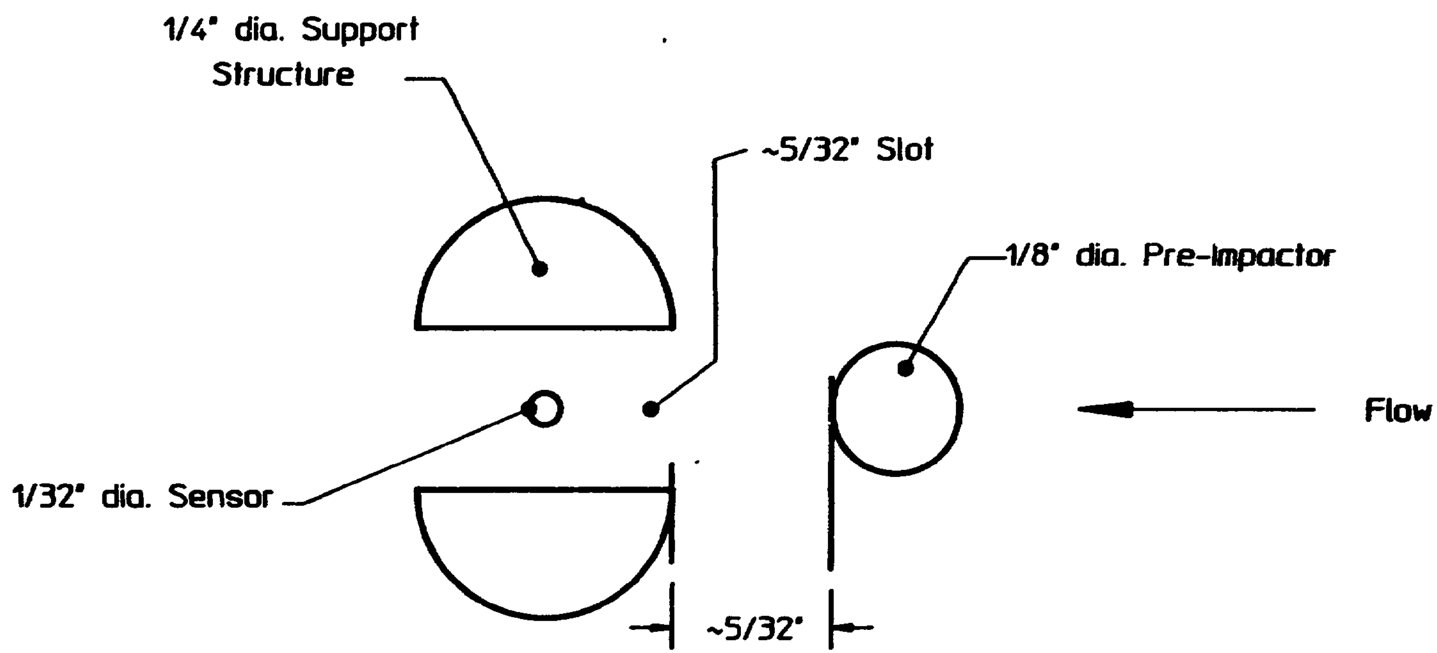

FIGURE A-3. CONFIGURATION OF EXTREL PROBE

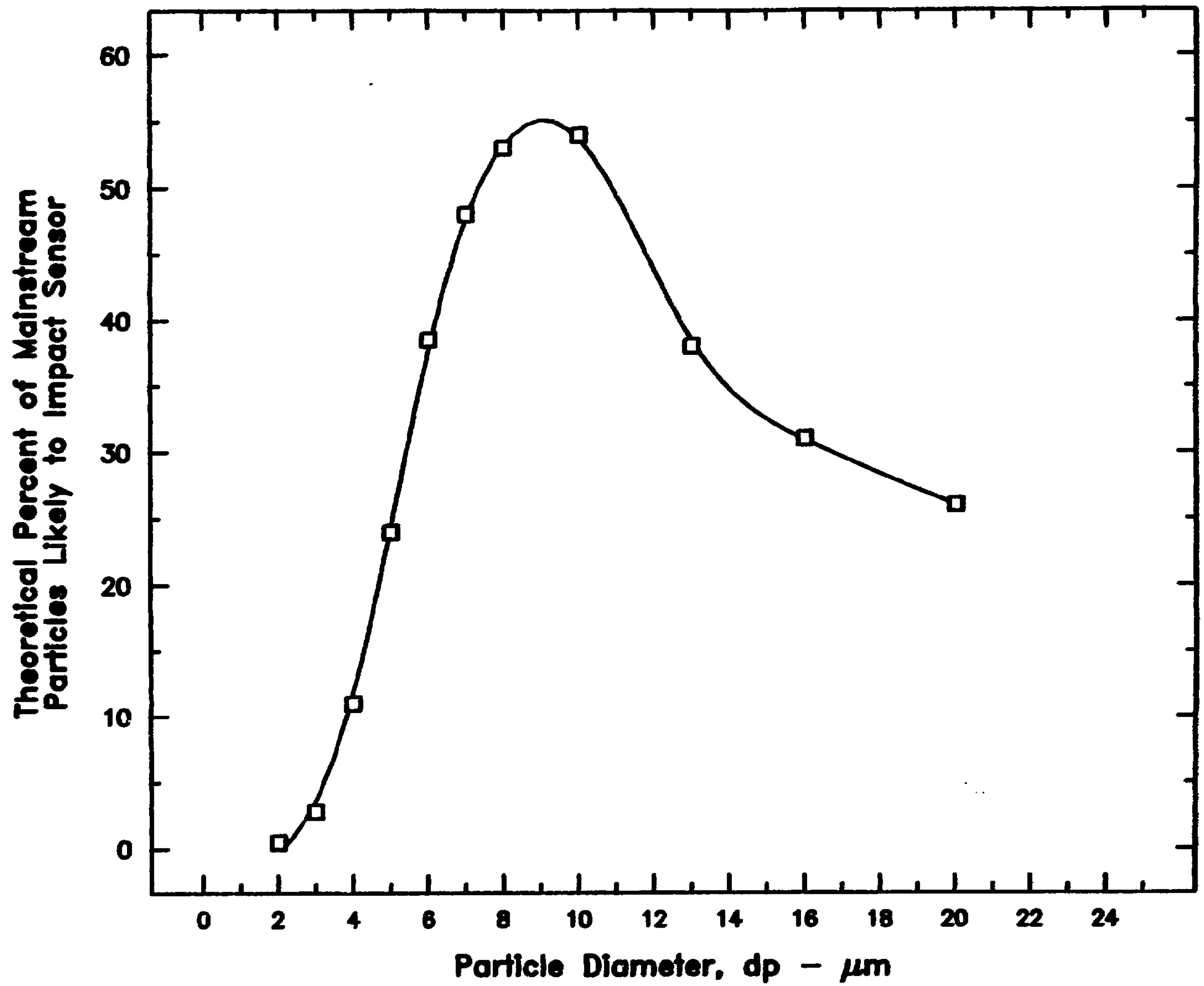

FIGURE A-4. THEORETICAL PERCENT OF MAINSTREAM PARTICLES LIKELY TO IMPACT EXTREL SENSOR AS A FUNCTION OF PARTICLE SIZE

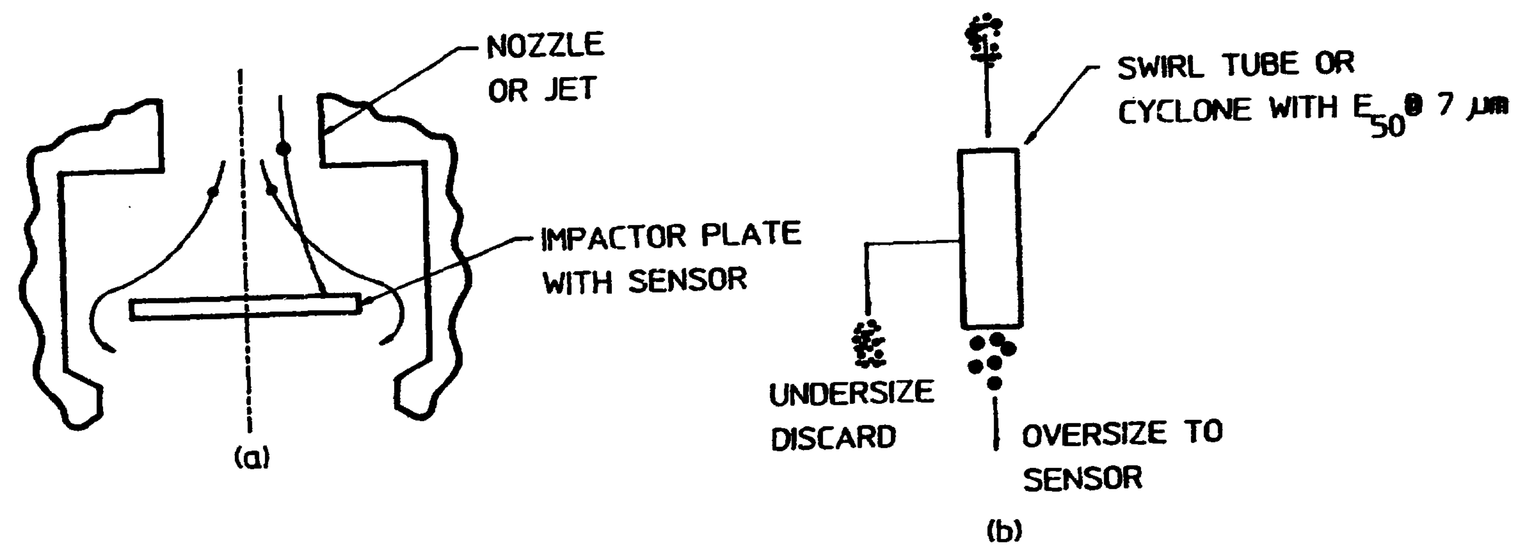

FIGURE A-5. POTENTIAL MODIFICATION OF EXTREL UNIT TO INCLUDE IMPACTOR PLATE WITH SENSOR

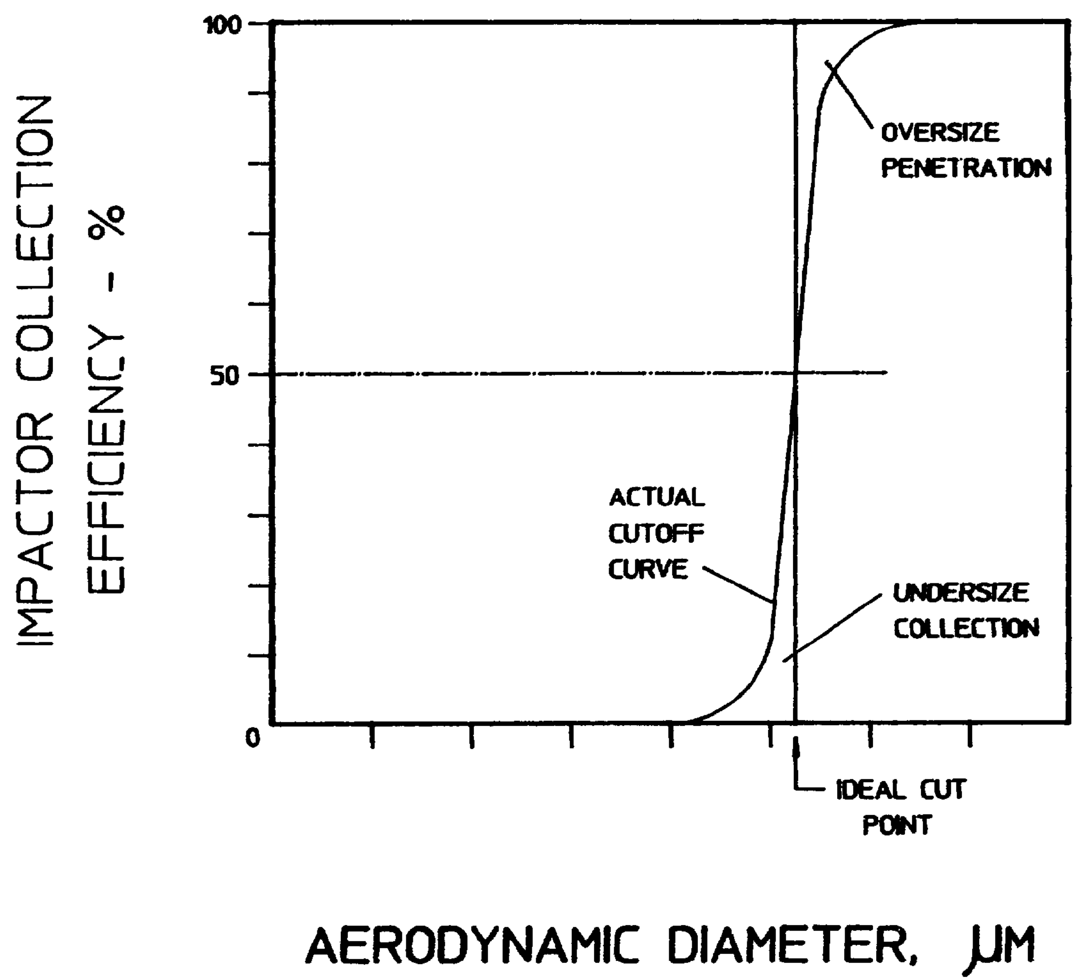

FIGURE A-6. IMPACTOR COLLECTION EFFICIENCY AS A FUNCTION OF AERODYNAMIC PARTICLE SIZE

out that the test set-up was designed to present (downstream) dust distributions to the probe that would simulate various degrees of filter operation ranging from normal to highly abnormal. In most cases, the specific size distribution and concentration level for a given test run were modified, based on the HIAC response, until the distribution in the test area matched the distribution of interest. An inherent requirement for proper size characterization is that the size distribution and concentration of the aerosol must remain relatively constant during the sampling period. This was accomplished by sampling for one-minute periods and making the necessary adjustments to keep repetitive samples within the same range for a given series of tests. For the most part, and depending on the specific type of dust loading being simulated, for instance, light to heavy, the results showed good repeatability from run-to-run.

Another inherent criteria is that the sample withdrawn by the sampling probe be representative of the aerosol at the point of sampling; that is, the sample must accurately represent the airborne concentration and particle size distribution of the test aerosol. In general, this is accomplished by isokinetic sampling, which matches the velocity at the probe tip with the velocity of the mainstream flow. This is necessary because inertial effects can cause the larger particles to deviate from the streamlines at the probe entrance in the presence of a velocity gradient. This can either enhance or diminish the concentration of particles entering the probe relative to the concentration in the mainstream. Once the particles are in the probe, additional losses can occur on internal walls during transport to the particle counter. EXTREL's comments on transport efficiency are discussed later in this appendix.

The efficiency of the sampling inlet; that is, the extent to which the inlet concentration matches the mainstream concentration, depends on the properties of the particles, particularly particle size, on the inlet dimensions and geometry, and on the flow conditions into the inlet and in the mainstream in the vicinity of the inlet. During testing, sampling was accomplished from a ducted flow with the probe directed upstream near the longitudinal centerline. The walls at the inlet were made thin so that the probe would have negligible influence on the flow conditions at the inlet. The probe's dimensions were set to provide isokinetic or near-isokinetic conditions at the inlet, based on a constant sampler flow rate.

The influence of transport losses on the overall results was investigated by comparing the transport characteristics of the probe used during the EXTREL tests with those of another (supposedly less objectionable) probe under similar conditions. This was done by sequentially counting the particles transported by each probe under the same set of test conditions. The actual counting sequence was, as follows:

.
.
.
na
nb
(n+1)b
(n+1)a
(n+2)a
(n+2)b
.
.

where n is the run number. Therefore, it can be seen that the probe's sampling line was switched at the sensor after every two (1-minute) runs. (The sample lines from each probe to the sampler were identical and of the same material and length -- 2 feet -- as used in the EXTREL tests.) In this manner, it was possible to compare results obtained between the two probes, as well as results for the same probe on a back-to-back basis. This provided a good control for the experiment in that one would expect a fairly high degree of consistency on back-to-back runs when using the same probe for a given set of aerosol conditions.

The theoretical transport efficiency for each probe is shown in Figure A-7. The curve for Probe B, which is the probe used during the EXTREL tests, indicates that no particles larger than 10μm should be counted by the HIAC, regardless of the particle size of the aerosol entering the probe. This, of course, was not the case, as numerous particles greater than 15μm were counted during testing. Also shown in the figure are curves for the theoretical and actual (measured) ratios for the number of particles transported by Probe A to the number of particles transported to Probe B, as a function of particle size. When both probes deliver a representative sample, this ratio will be equal to one. Values of Γ for each HIAC channel, for nineteen consecutive test runs is given in Table A-1. It can be seen that excellent correlation ($\Gamma \sim 1$) was obtained through the first four channels (0.5 to 10.0μm) even though the theoretical transport efficiencies for the two probes were significantly different over this range. It is particularly noteworthy that the correlation is best (in terms of $\Gamma \sim 1$ and $\Delta\Gamma$ being relatively small) for channel 4, since this covers the 5 to 10μm size range, which includes the 7μm threshold. Correlation was least for channel five, covering the 10 to 15μm range. Correlation for channel six (> 15μm; 10 to ~ 20μm) was fairly good. Overall, at the higher end (> 10μm), the ratio of particles transported by Probe A to those

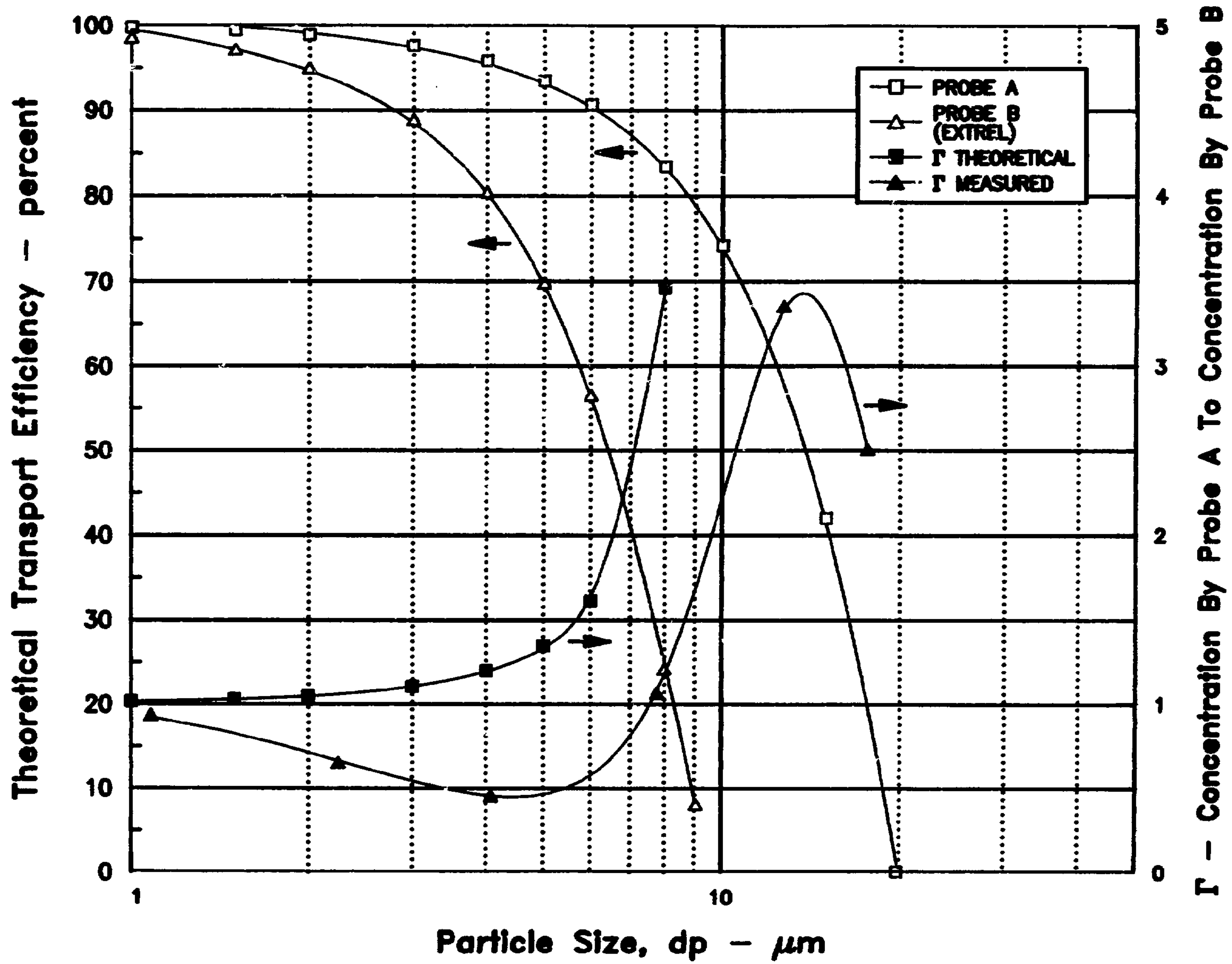

FIGURE A-7. THEORETICAL TRANSPORT EFFICIENCY AND THEORETICAL AND ACTUAL TRANSPORT RATIOS FOR PROBES A AND B AS A FUNCTION OF PARTICLE SIZE

TABLE A-1. RATIO OF CONCENTRATION MEASURED BY PROBE A TO THE CONCENTRATION MEASURED BY PROBE B

Run	1 .5-1.5 (1.08)	2 1.5-3.0 (2.33)	3 3-5 (4.08)	4 5-10 (7.77)	5 10-15 (12.7)	6 >15μm (17.6μm)	Channel Channel Range Adjusted Midpoint
9	.93	.88	.79	1.10	3.60	3.75	Conditions:
10	.92	.85	.77	1.17	3.81	3.85	
11	.92	.89	.82	1.11	3.60	2.92	Normal PC (2.5)*
12	1.04	1.01	.82	1.11	3.57	3.11	(16%)**
13	.97	.97	.85	1.08	3.24	3.00	V_m = 17.5 fps
14	.91	.85	.76	1.11	3.03	2.32	
15	1.00	.98	.86	1.08	3.41	3.84	
16	.92	.88	.83	1.05	3.55	2.16	Normal PC (2.5)
17	.87	.83	.79	1.05	3.40	2.00	(21%)
18	.90	.89	.83	1.05	3.99	2.20	V_m = 13 fps
19	.89	.83	.79	1.04	3.72	2.95	
20	.94	.90	.84	1.04	3.44	2.26	Moderate PC (1.6)
21	.99	.98	.92	1.02	2.90	1.79	(16%)
22	1.06	1.06	1.00	1.00	2.64	1.51	V_m = 13 fps
23	1.00	.95	.89	1.01	3.23	2.50	
24	.97	.94	.83	1.02	2.98	2.49	
25	1.48	1.58	1.26	1.21	3.00	1.97	Low PC (0.9)
26	1.30	1.42	1.15	1.11	2.65	1.72	(9%)
27	1.32	1.43	1.19	1.12	2.72	1.43	V_m = 17.5 fps

* Precleaner setting (higher number means larger precleaner airflow).
** Precleaner airflow as percent of main airflow in sampling area.

transported by Probe B, based on theoretical transport efficiencies, should trend toward infinity. In practice, these values ranged from a little over 1 to a high of 4.

Adjusting the data based on the transport efficiency of Probe A only shifts the $\Delta N/\Delta \log dp$ vs dp curves slightly, as shown in Figure A-8. When the data are considered with respect to the particle size and concentration threshold levels, and with respect to the typical downstream distributions encountered with operating filters, the impact of this shift is negligible. Previous testing with full-scale filters showed that there is a high statistical likelihood that, because of the nature of typical environmental dust distributions, detection at the 7μm level will adequately account for the presence of larger particles even though the larger particles will be present at much lower concentrations. As has been shown, sampling with the probe used during the EXTREL test (Probe B) provided good agreement, particularly in the 5 the 10μm area, with the samples obtained with Probe A, which had a theoretical transport efficiency of 94 to 74 percent in this range. The comparative laboratory test of the two probes has shown that the theoretical transport efficiency for Probe B, as calculated by Stokes Number, is much too low compared to actual practice. Furthermore, particles exceeding 15μm were measured even though the theoretical cut-off was calculated at about 10μm. It is quite likely that the actual transport efficiency for Probe A is also higher than the theoretical prediction. It can be concluded that in all cases, the probe had little, if any, impact on the test results.

EXTREL's conclusion that it is not necessary to measure dust concentration is not correct. Concentration is the correct parameter because it tells the number of particles, at a given size, that can potentially enter the engine for each cubic foot (or other specific volume) of air inducted by the engine. Therefore, particle concentration is directly related to potential engine wear. Furthermore, concentration is directly related to filter performance. For example, most test procedures specify the upstream concentration (g/m^3 or g/ft^3) that must be presented to the filter during initial efficiency, cumulative efficiency and dust capacity testing. By specifying a particular concentration level for a given dust type, such as AC Fine or Coarse, the results are normalized so that the upstream environment is the same for all vehicles and systems in any given situation. In the same manner, the downstream concentration is a direct measure of the number of particles that have penetrated the filter system and, depending on the specific concentration level involved, represents a direct correlation to the status of the filter. In short, the concentration measurement normalizes the data so that it is no longer engine specific. Therefore, as concentration normalizes the testing of air filter systems, so does it normalize the presence of downstream particles for a given filter condition.

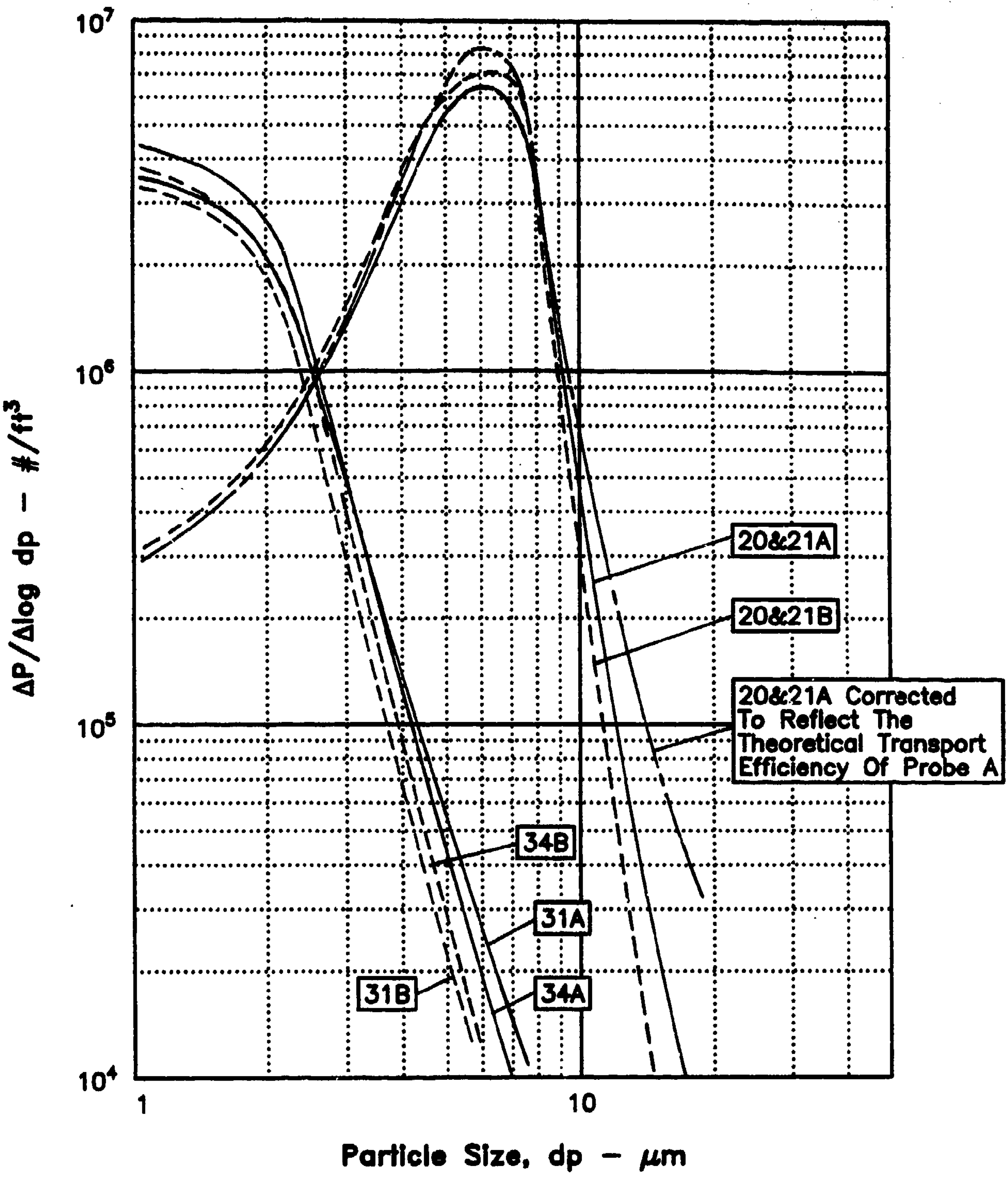

FIGURE A-8. COMPARISON OF TEST DATA BEFORE AND AFTER CORRECTION TO REFLECT THEORETICAL TRANSPORT EFFICIENCY OF PROBE A

APPENDIX B

ERROR ANALYSIS OF PARTICLE COUNTS IN DISTURBED FLOWS

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November 30, 1988

ERROR ANALYSIS OF PARTICLE COUNTS IN DISTURBED FLOWS

Abstract

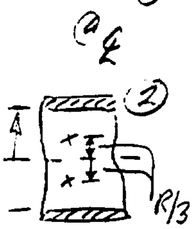
The performance of particle counter of small solid particles in clean air environment is evaluated. The air samples are assumed to be obtained through a probe with one, two, and three orifices from a pipe flow. The flow is assumed to be an inlet turbulent pipe flow, a fully developed turbulent pipe flow, and a turbulent S-pipe flow with a 90^0 inlet bend and a 90^0 outlet bend. The first two geometries represent the most conventional systems, while the last geometry represents a complex case with largest possible errors. The estimated error is evaluated as the ratio between the particle count from the sample air over the calculated total particle count in the pipe flow. The results obtained indicate the maximum possible error in the measurement of the particle counter in the different geometries and flow conditions.

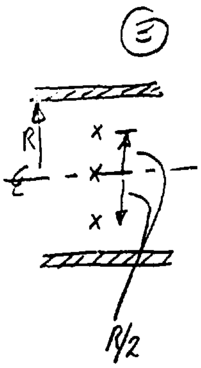
Foreword

Measurements of particle concentrations, velocity, and size distribution are of considerable interest for environmental control[1]. Air-solid particle flows is a particular class of two-phase flows in which small particles are suspended in the air. The flow of each phase is governed by the relationships obtained from the conservation of mass, momentum, and energy.

Objective

The main objective of this present effort is to make an engineering analysis to determine the difference between the particle count in samples of dusty air and the total air flow inside a pipe. The samples are obtained with a probe aligned with the plane of symmetry of the flow in complex geometries. The probe is analyzed under three different conditions. In the first case, the probe has one orifice located in the middle of the pipe and normal to the pipe axis. In the second case, the probe has two orifices located equally distributed along the pipe diameter, that is R/3 distance from the pipe axis where R is the pipe radius. In this case, no samples are obtained from the center of the pipe where larger velocity magnitudes are expected. In the third case, the probe has three orifices equally ditributed along the pipe diameter, that is one of them in the pipe center and the other two at R/2 distance from the pipe center.





The inlet pipe flow is analyzed in three different geometries. In the first one, the inlet is assumed open to the air environment at a distance less than 20 pipe diameters. In the second one, the inlet flow is assumed fully developed turbulent pipe flow. In the third case, the inlet is assumed to be connected to a 90^0 bend pipe and the outlet is assumed to be connected to another 90^0 bend pipe in the oposite direction.

This different flow geometry conditions and sample origin provide an effective guidance in the estimation error in the particle count from the samples.

RELATIVE PARTICLE DENSITY MEASUREMENT

The air environment is assumed to be composed of pure air and small solid particles. In this engineering analysis, the particles are assumed diluted and the air flow is not affected by the presence of the particles. If larger particles were present in the fluid they can be detected with less difficulty. If the particles are assumed small and uniform, the particle count is directly proportional to the relative particle density (particle mass / mix volume), and the ratio of the sample and exact value is the same in both cases. For small amount of particles, the particle velocity is approximately equal to the air velocity and the particles are carried by the air flow.

* EXACT RELATIVE PARTICLE DENSITY:

The total relative particle density of the air flow inside the pipe is defined as follows,

$$P_E = \frac{\int_A P \cdot V \; dA}{\int_A V \; dA} \quad \text{(lbm-particles/cu ft-mix)} \qquad (1)$$

* SAMPLE RELATIVE PARTICLE DENSITY:

The sample relative particle density is defined as follows,

$$\hat{P}_N = \frac{(1/N)\sum_{s=1}^{N}(P \cdot V)_s}{(1/N)\sum_{s=1}^{N}(V)_s} \quad \text{(lbm-particles/cu ft-mix)} \qquad (2)$$

where N is the number of sample orifices in the probe,

P_s is the local relative particle density of the sample from orifice s,

V_s is the local velocity magnitude in the orifice s of the probe, and

A is the area of the pipe in the test section.

* NONDIMENSIONAL ERROR SAMPLE PARAMETER:

The nondimensional relative error sample parameter is defined as follows,

$$E = P_N / P_E \qquad (3)$$

thus if the sample value is equal to the exact value then E=1.

We should observe that the local relative particle densities are weighted with the local flow velocity in order to reflect the fact that a fixed volume sample obtained from a probe with several orifices will contain more fluid obtained from the orifices with larger local flow velocities.

RESULTS

CASE 1. TURBULENT INLET PIPE

Experimental observations show that the velocity and the relative density distributions are nearly uniform in sections close to the entrance of the pipe. The distributions vary along the inlet lenght untill they reach the fully developed profiles observed in turbulent pipe flows. The inlet lenght development distance is found to be about 50 to 100 pipe diameters[6]. In some particular cases, the minimum inlet lenght has been found to be about 25 pipe diameters[7,9].

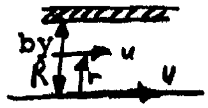
Assuming that the entrance lenght of the pipe is less than 10 diameters, the velocity and relative density profiles are nearly uniform and the estimated error sample parameter is

$$E = 1 \tag{4}$$

Assuming a small boundary layer in the flow velocity and the relative particle density profiles, the estimated error increases slightly to values less than 1.05 and is negligible.

CASE 2. FULLY DEVELOPED TURBULENT PIPE FLOW

Experimental observations indicate that the velocity profile in fully developed turbulent pipe flows is well represented by the empirical equation



$$u/U = (1 - r/R)^{1/n} \tag{5}$$

r/R	u/U
.1	.995
.2	.969
.3	.950
.4	.930
.5	.906
.6	.877
.7	.84
.8	.795
.85	.763
.9	.72
.95	.6
.975	
.985	

where u is the local flow velocity,

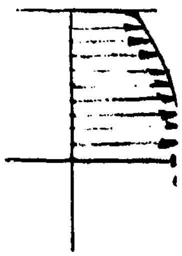
U is the flow velocity at the center of the pipe,

r is the radial distance of the position of u,

R is the pipe radius, and

n is an empirical exponent whose value is a function of the Reynolds number of the pipe flow, n = 7 in smooth pipes with Reynolds numbers of the order 10^5.

The profile of the relative particle density is found to be a function of the velocity profile. In this engineering analysis, this profile is assumed to be proportional to the ratio of the local velocity and the mean pipe velocity elevated to the power m.



$$P/\overline{P} = (u/\overline{U})^m \tag{6}$$

The exact relative particle density is found to be

$$P_E = (U/\overline{U})^m (n+1)(2n+1)/((m+n+1)(m+2n+1)) \tag{7}$$

The error sample parameter with the single orifice probe located in the center of the pipe is E_1,

$$E_1 = (m+n+1)(m+2n+1)/((n+1)(2n+1)) \tag{7}$$

while the error sample parameter obtained with the probe with two orifices is

$$E_2 = (2/3)^{m/n} E_1 \tag{8}$$

and with three orifices is

$$E_3 = ((1+2(0.5)^{(m+1)/n})/(1+2(0.5)^{1/n}) E_1 \tag{9}$$

For the empirical value of n = 7 and the following values of the parameter m = 0,1,2,3, and 10, the following Table shows the values of the error sample parameter in the case of fully developed turbulent pipe flow.

TABLE 1. ERROR PARAMETER IN FULLY DEVELOPED PIPE FLOW

m	0	1	2	3	10
E_1	1.	1.20	1.42	1.65	3.75
E_2	1.	1.13	1.26	1.39	2.10
E_3	1.	1.12	1.25	1.38	2.23

The results show that when m=0 the relative density profile is uniform and the error parameter is 1 independent of the number of orifices in the probe, as it should be. Increasing values of m increases the particle concentration X in the pipe center and higher error parameter values are obtained. Increasing the number of orifices tend to decrease the values of the error parameter, however only the cases with 1 and 3 orifices include sample fluid from the pipe center with larger particle concentrations. We should observe that in all these cases the values of the error X parameter are within the same decade of order of magnitude.

NUMERICAL SIMULATION

In order to test the numerical method for further complex system configurations, a preliminary numerical computation of a two-dimensional channel flow was performed. Figure 1 shows the 46x89 mesh and Figure 2 shows the velocity profile at different sections. This simulations solve the conservation of mass, momentum, and energy equations. The inflow boundary conditions are no change of entropy, enthalpy, and tangential velocity component when solving along the flow direction. The outflow boundary condition assumes no change in outflow pressure, while the other conditions are properly extrapolated. No slip conditions and adiabatic wall conditions are used in finite difference toward the wall mesh points. The turbulence model of Baldwin and Lomax (1967) is employed to close the system of equations[11].

The velocity profile obtained from this simulation was used to calculate the error parameter in the measurement of the relative particle density. The results are of similar order ~~than~~ to those shown in Table 1. with values slightly closer to the value 1.

CASE 3. TURBULENT S-BENDED PIPE FLOW

Although this is a simple geometrical configuration, a straight pipe with a 90^0 bend pipe in the inlet and the outlet of the straight section, the flow is quite complex. The flow is turbulent and include flow separations in the outer zones of the bend sections. This configuration provides a case where the velocity distribution includes two symmetric secondary recirculations across the pipe section. In the plane of symmetry the flow is asymmetric with respect to the pipe axis. The air pressure, density, and temperature are nearly constant across the pipe in the straight test section. However, the particle concentration varies as well as the flow velocity.

NUMERICAL SIMULATION

In order to obtain the flow velocity data, a preliminary numerical simulation was carried out of a two-dimensional S-shaped channel flow, similar to the one previously described in the pipe flow. Figure 3 shows the 69x31 computational mesh geometry, while Figure 4 shows the velocity profiles at different sections of the pipe. Following the procedure used in the analysis of the pipe flow, the error parameter of the relative particle density was calculated considering the probe with 1, 2, and 3 orifices. The relative particle density distribution is also assumed proportional to the velocity profile.

TABLE 2. ERROR PARAMETER IN TURBULENT S-BENDED PIPE FLOW

m	0	1	2	3	10
E_1	1.	1.34	1.74	2.18	5.66
E_2	1.	1.17	1.35	1.50	2.01
E_3	1.	1.24	1.50	1.77	3.40

The results are consistent with the pipe flow of Case 2 with similar order of magnitude values. For uniform particle distribution, m=0, the error parameter is 1 independent of the number of orifices. Under increasing values of the parameter m, more skewed particle distribution profiles, the error parameter values increases. Increasing the number of orifices decreases in general the error parameter. Again we should observe that the case with two orifices, E_2, does not include fluid from the pipe center. and it is not reccomended because it may miss large concentration of particles. Figure 5 shows the relative particle density distribution in the test section. These profiles show a broad core pipe section with signifficant concentration of particles. Thus it is not surprising that all values of the error parameter shown in Table 2 are of same order of magnitude, although with signifficant differences.

what is E as f(part. size)?

FLOW PARAMETERS

The pipe is assumed to have a diameter of 3 inches, although the results reported are nodimensional and valid for other pipe dimensions. The flow is air with small suspended solid particles. The Reynolds number of the flow based on the pipe diameter is 4.6 10^5, the flow temperature is 860 ^{0}Rankine, and the mean flow velocity is of the order of 100 ft/sec. The Prandtl number is assumed to be 0.7 and the specific heat ratio 1.4.

The Reynolds number is much larger than the critical Reynolds number 2000 of transition to turbulent pipe flow.

400°F – much higher than for inlet air flows, even @ portions w/in engine compartment

$Q = VA \cong 100 \frac{ft}{sec} \frac{\pi}{4}\left(\frac{3}{12} ft\right)^2 \frac{60 sec}{min}$

~300 cfm

$N_{Re} = \frac{\rho V d}{\mu}$

ρ & μ are $f(t)$

$\times 10^{-2}$ P = 10^{-2} [g/cm·s]

	μ		ρ_{air}	
μ_{air} @ 20°C	1.81×10^{-2} cp	(68°F)	1.205×10^{-3} g/cm³	(.075 lb/ft³)
60°C	1.20×10^{-2}	(140°F)	1.05×10^{-3}	.065
100°C	2.17×10^{-2}	(212°F)	$.96 \times 10^{-3}$	
200°C	2.60×10^{-2}	(392°F)	$.72 \times 10^{-3}$	

ρ/μ @ 60°C $\frac{1.05 \times 10^{-3}}{1.20 \times 10^{-2}} = .088$

@ 200°C $\frac{.72 \times 10^{-3}}{2.60 \times 10^{-2}} = .028$

200°C vs 60°C → N_{Re} ~ 3 N_{Re} > 2K

MBT

CONCLUSIONS

The engineering analysis of the error parameter in the particle count of air samples in comparison with air environment has been completed in its first phase. The analysis of the turbulent flow is based in an inlet pipe, a fully developed pipe, and an S-bended pipe flow. The sample probe is considered with one, two, and three orifices equally distributed along the pipe diameter. The flow velocity profile has been obtained from known empirical observations and/or preliminary numerical simulations. The distribution of solid particles in the flow depends on different flow conditions and past history of the flow, this analysis assumes that the particle distribution is proportional to the flow velocity distribution elevated to a power m. The power parameter has been analyzed with different small and large values (0 through 10), representing from uniform distribution to a very skewed profile.

This preliminary analysis indicates that the error parameter varies from values of 0.8 through 6.0 where the unity value represents the exact air environment value. The location of the sample orifices in the pipe flow is important, and the results show that one orifice should be located at the center of the pipe. If more precision is required, two additional orifices should be added.

Lastly, since the more complex results of the S-bended pipe flow are based on very basic preliminary numerical simulations, it is reccomended that further simulations be carried out including the effect of the viscous drag forces on the air flow

and the changes in particle concentration due to these forces. The analysis should also consider the three-dimensionality of the flow or at least the three-dimensional effects on the plane of symmetry of the systems.

The results of these kind of simulations are feasible at relativity very low cost and provide the needed tests of the performance of the particle count in clean manufacturing environments.

Finally, we show in Figures 6 through 8 a graphical presentation of the sample error obtained in each flow studied in this report. The error is a function of the particle distribution parameter m, where m=0 is a uniform distribution and m=10 is a very skewed distribution. The maximum error in all cases is less than 500%, considering the assumptions mentioned above.

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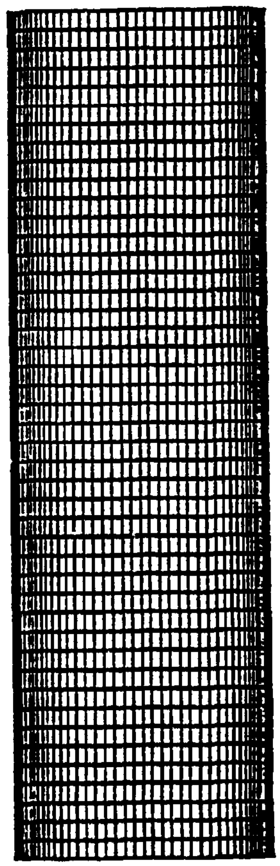


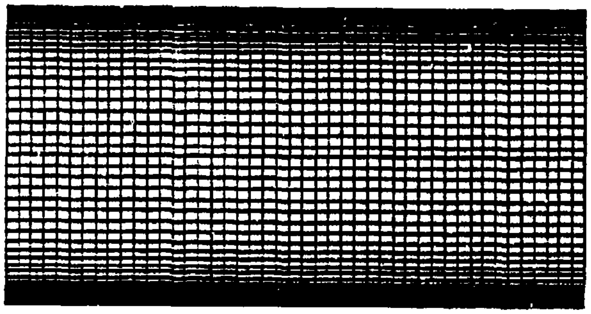


Figure 1. Section of computational mesh of pipe flow.

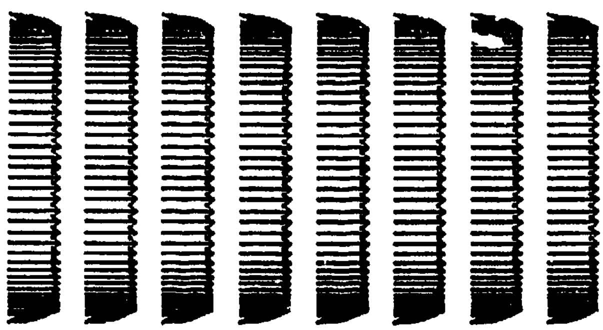


Figure 2a. Initial velocity profile of Fig. 1.

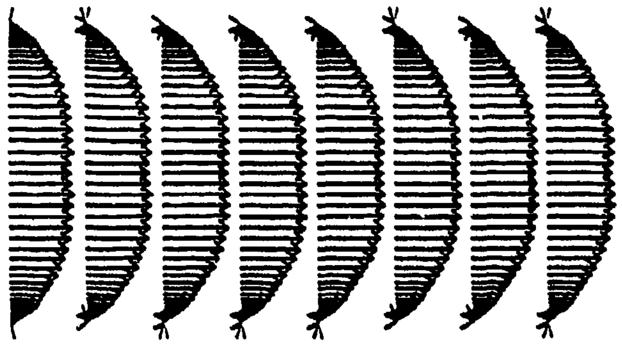


Figure 2b. Final velocity profile of Fig. 1.

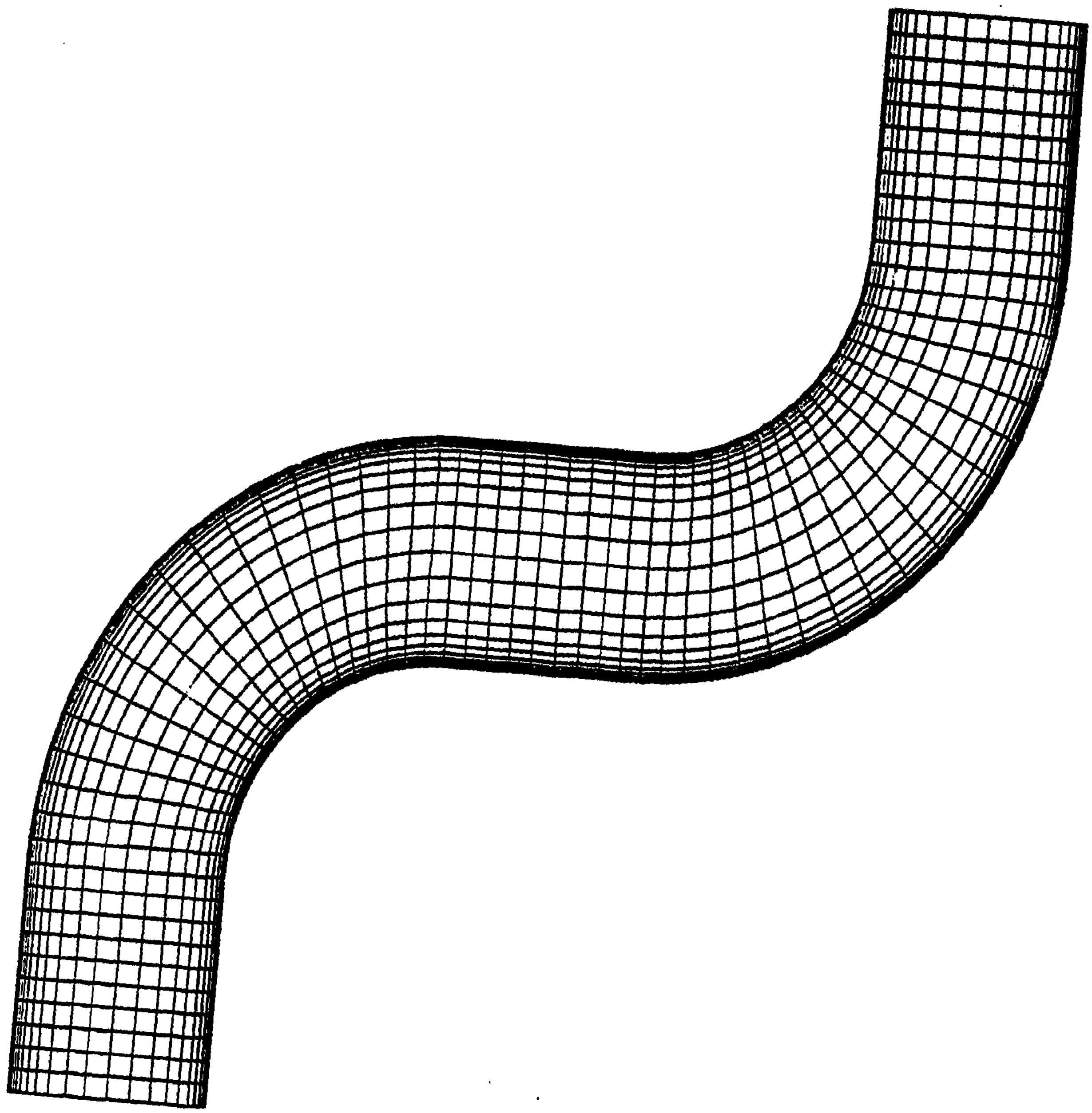


Figure 3a. Computational mesh of S-bended flow.

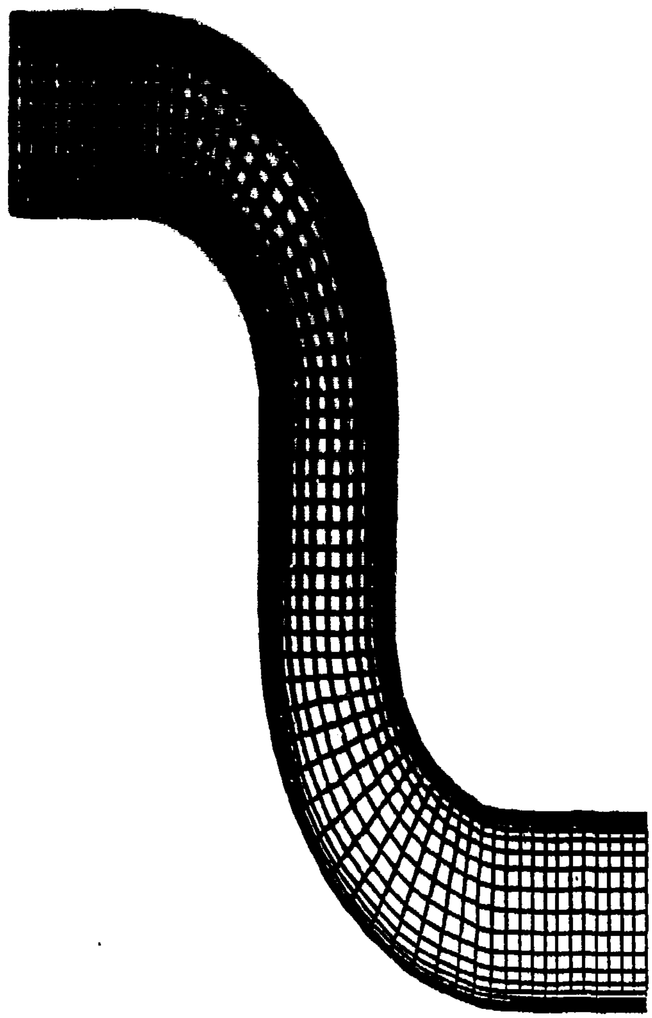


Figure 3b. Same computational mesh shown in previous Fig. 3a. The figure has been amplified by the postscript post-processor.

Figure 4a. Initial velocity profile corresponding to Fig. 3b.

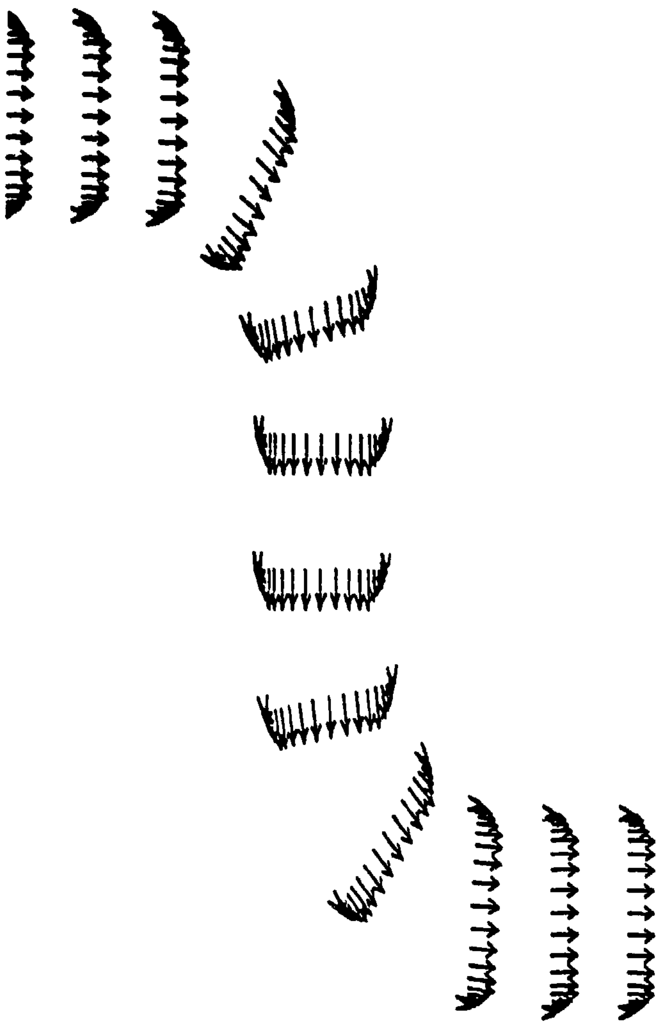
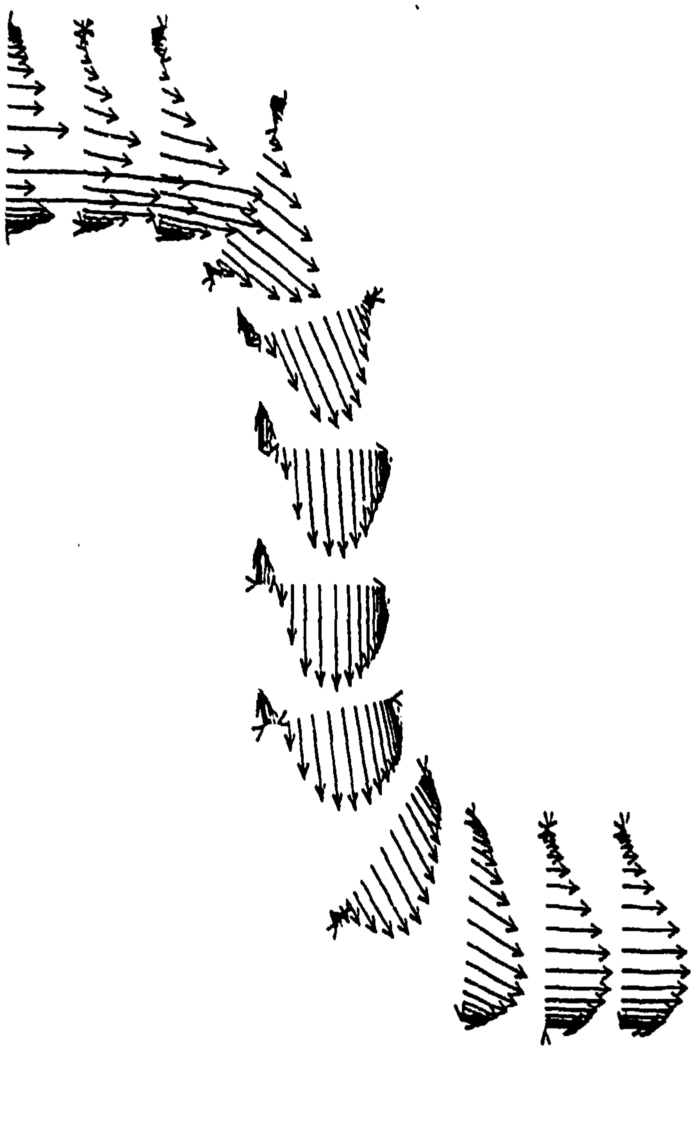


Figure 4b. Final velocity profile corresponding to Fig. 3b.



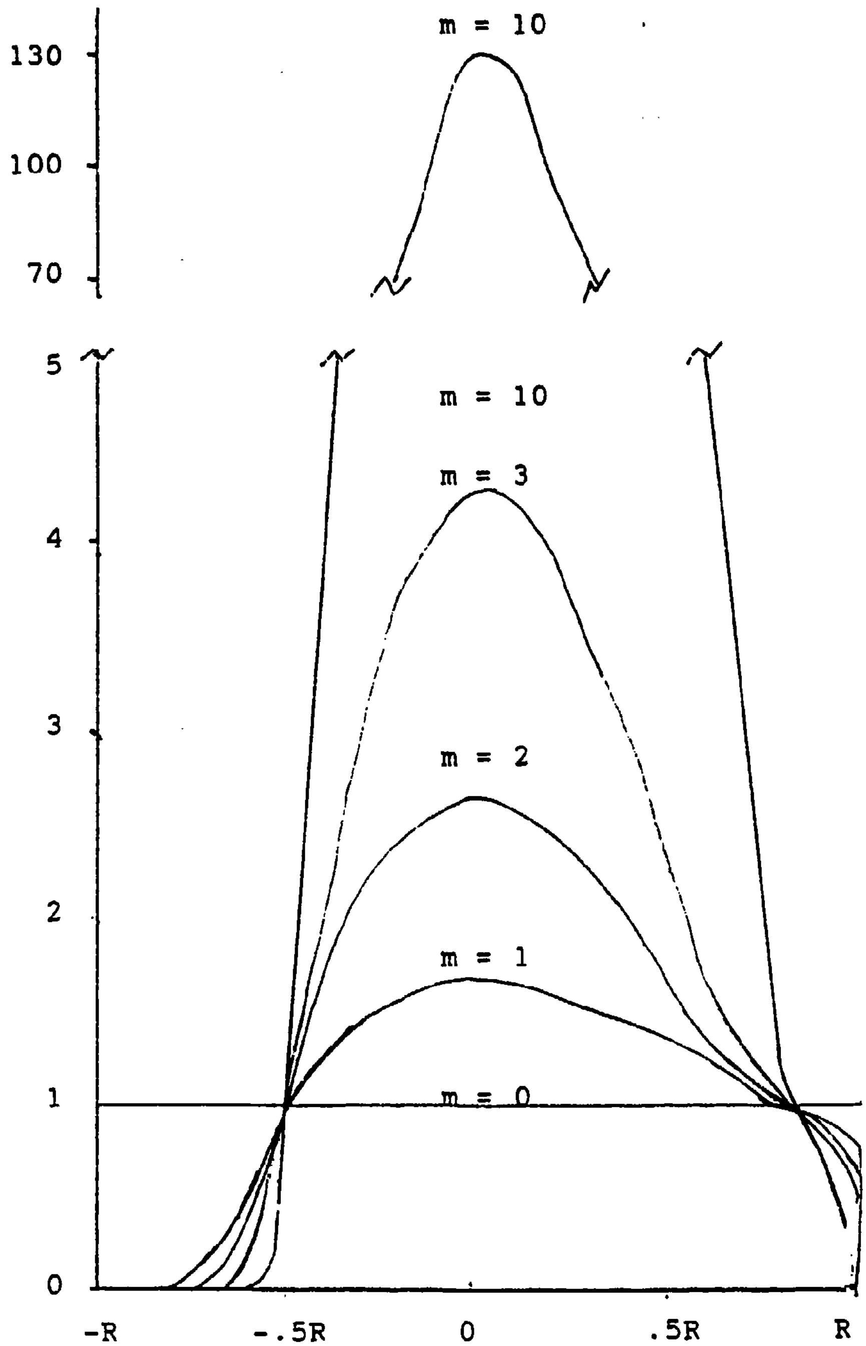


Figure 5. Relative particle density distribution along the symmetry plane in the test section of the S-bended pipe flow.

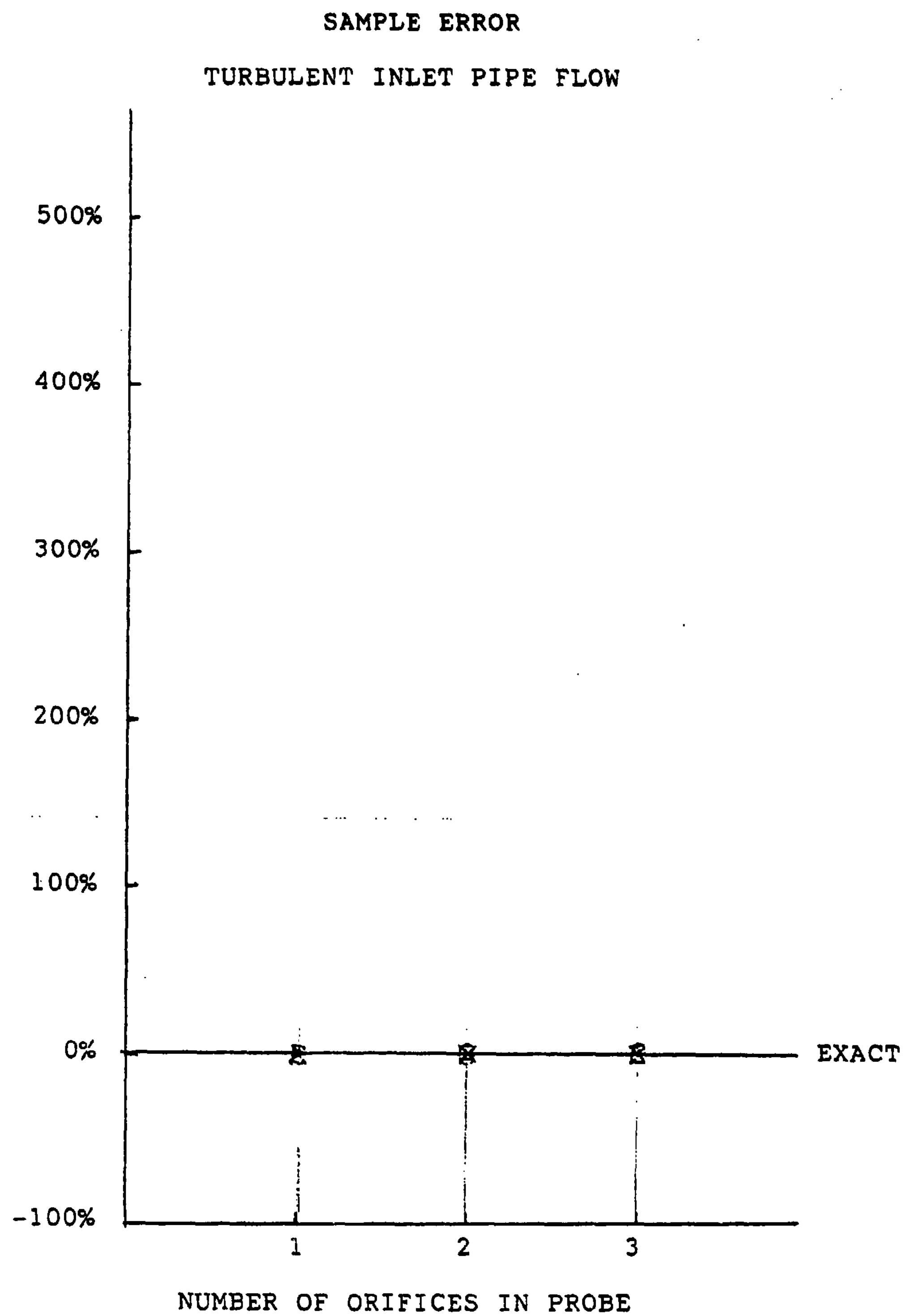
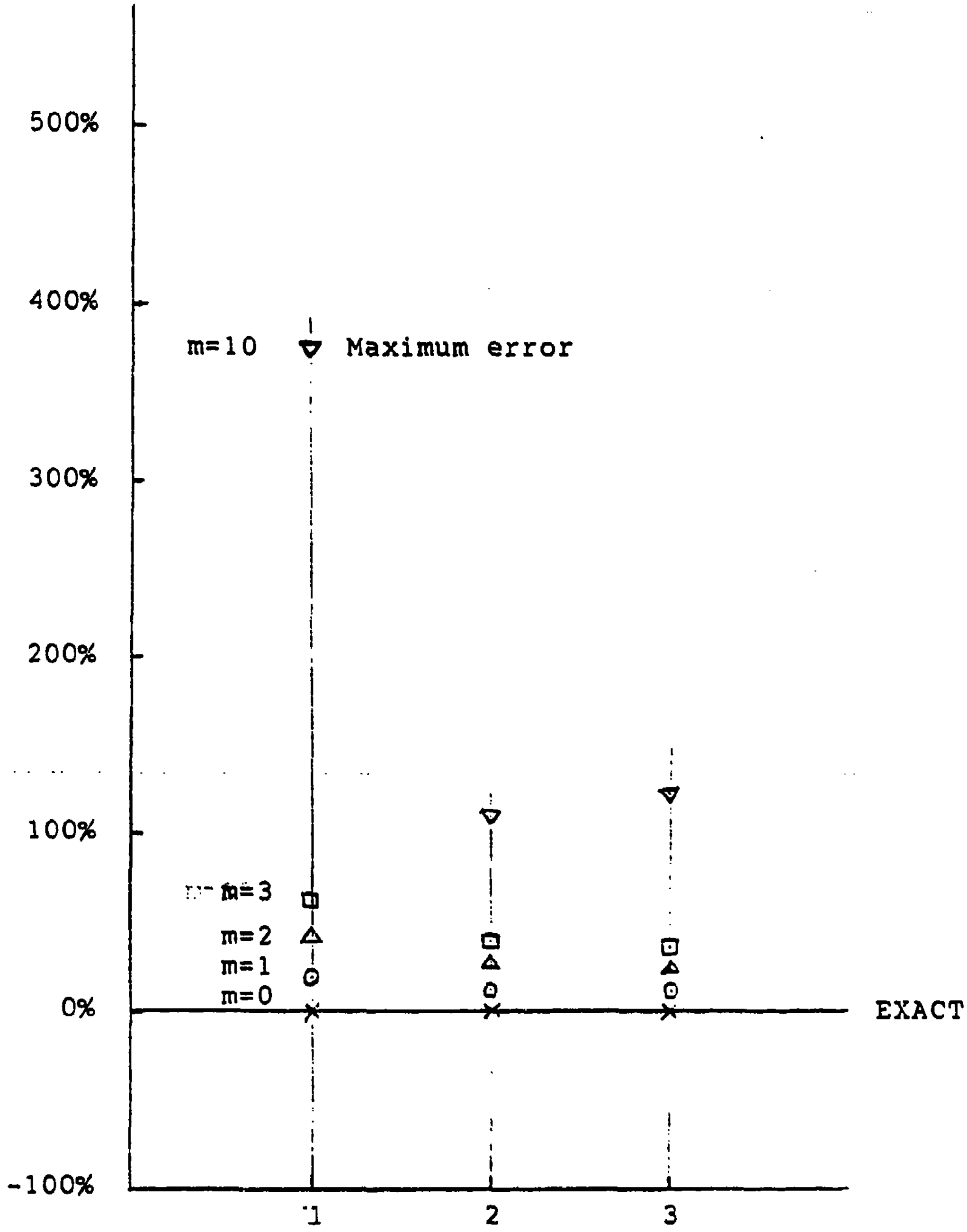


Figure 6. Sample error in turbulent inlet pipe flow.

SAMPLE ERROR

FULLY DEVELOPED TURBULENT PIPE FLOW



NUMBER OF ORIFICES IN PROBE

Figure 7. Sample error in fully developed turbulent pipe flow.

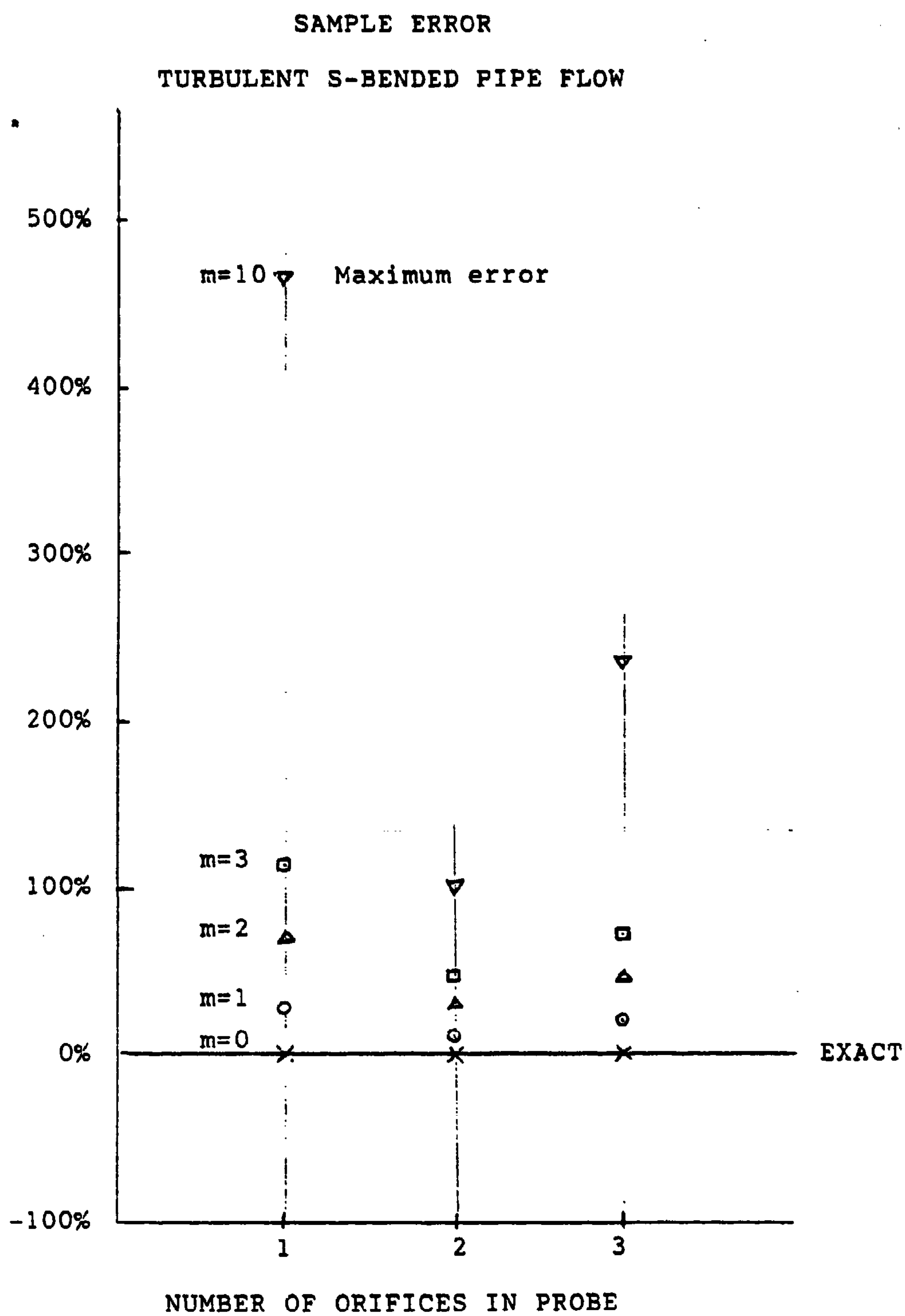


Figure 8. Sample error in turbulent S-bended pipe flow.

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Mawby, Patricia

From: Margrif, Frank [MargrifF@tacom.army.mil]
Sent: Wednesday, May 09, 2001 3:00 PM
To: 'pmawby@dtic.mil'
Subject: FW: Distribution Statement Change for Two (2) TARDEC Technical Re ports

Pat: I tried to forward this message to Larry Downing but got a message back address unknown, fatal error. Obviously something went wrong. Could you please check this out. I would appreciate it. I used the e-mail address you gave me. Maybe you could forward it to him.

Frank

-----Original Message-----
From: Margrif, Frank
Sent: Wednesday, May 09, 2001 2:12 PM
To: 'idowning@dtic.mil'
Cc: Raffa, Charles; Mushenski, Mark 'WGM'; Kuhn, David
Subject: FW: Distribution Statement Change for Two (2) TARDEC Technical Re ports

Mr. Larry Downing:

As explained in the two messages sent below, we are requesting that the Distribution Statement on these two (2) reports be changed to: "DISTRIBUTION STATEMENT A: APPROVED FOR PUBLIC RELEASE; DISTRIBUTION IS UNLIMITED". In this way potential contractor hopefully will be able to get copies of the reports if they need too through your office.

I sent through the mail last Friday (6 May) one (1) copy of each report to Pat with the changed Distribution Statement. However, Pat informed me in her last message that she found both reports in the database with the appropriate AD numbers. Thus, your reports need to be updated to new distribution statement.

Our legal office at TACOM informed me that the project engineer can decide when the reports can have the Distribution Statement changed. I and another engineer Mr. Mark Mushenski are considered the project engineers on these reports and we have both agreed that the Distribution Statement should be changed to "A".

Hope this can be accomplished and meets with your approval.

Thanks for your effort in this matter. Please contact or reply to me if there are any questions.

Frank Margrif
Propulsion Product Support Team
Research Business Center
Comm (810) 574-5796
DSN 786-5796
FAX -5054

-----Original Message-----
From: Raffa, Charles
Sent: Wednesday, May 09, 2001 10:26 AM
To: Margrif, Frank
Cc: Mushenski, Mark 'WGM'
Subject: FW: Distribution Statement Change for Two (2) TARDEC Technical

Re ports

-----Original Message-----
From: Mawby, Patricia [mailto:PMawby@DTIC.MIL]
Sent: Tuesday, May 08, 2001 7:51 AM
To: 'Raffa, Charles'
Subject: RE: Distribution Statement Change for Two (2) TARDEC Technical
Re ports

Charles,

I found both of your reports in the database. DTIC has DAAE07-89-C-R011, Phase II, with our AD number as ADB159687 and your March 1991 as ADB159757. If you only need the distribution changes a letter to our Security Officer should be OK. His name is Larry Downing, (703) 767-0011 and his email is: ldowning@dtic.mil. If you have any questions, please call. If we looked before, I don't know why they weren't found. Again, I hope this hasn't caused you any problems.

Pat
(703) 767-9038

-----Original Message-----
From: Raffa, Charles [mailto:RaffaC@tacom.army.mil]
Sent: Monday, May 07, 2001 5:30 PM
To: 'Pmawby@dtic.mil'
Cc: Kuhn, David; Mushenski, Mark 'WGM'; Margrif, Frank
Subject: FW: Distribution Statement Change for Two (2) TARDEC Technical
Re ports

> -----Original Message-----
> From: Margrif, Frank
> Sent: Friday, May 04, 2001 1:15 PM
> To: Daniska, Lyn
> Subject: Distribution Statement Change for Two (2) TARDEC Technical
> Reports
>
> Lyn; Could you put Charlie's title on and let him send this out to Pat.
> Her e-mail is pmawby@dtic.mil. Also send copy to David Kuhn and Mark
> Mushenski.
>
> Thanks ,Frank
>
> 06 May 01
>
>
>
>
> Ms. Pat Mawby;
>
> Two (2) Technical Reports from TACOM/TARDEC were published over ten (10)
> years ago containing Distribution Statements either B or C which limited
> their distribution. The title of reports are as follows: (1) ENGINE INTAKE
> AIR DUST DETECTOR (U), (PHASE II), CONTRACT NUMBER DAAE07-89-C-R011,
> NOVEMBER 1990, (2) ENGINE INTAKE AIR DUST DETECTOR REQUIREMENTS AND

> PERFORMANCE, MARCH 1991.
>
> Per our discussion on 3 May 01, your office does not have a copy of either
> report. These reports need to become available for future contractors
> evaluation in helping them possibly prepare a Phase I SBIR proposal for a
> future dust detector for the new Abrams/Crusader engine. Therefore, the
> TARDEC project engineer has determined that both reports can be changed to
> a Distribution Statement A," approved for public release". We completed
> the distribution statement changes on each report and forward one (1)
> copy each to your office on 6 May 01.
>
> The POC for this action is Frank Margrif, tel:(810) 574-5796 or DSN
> 786-5796.
>
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>
>
> CHARLES J. RAFFA
>
> Associate Director
>
> TACOM
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